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EVALUATION OF

SETTLEMENTS AT THE

CONQUISTA TAILINGS

IMPOUNDMENT

APPROVED BY

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# EVALUATION OF SETTLEMENTS AT THE CONQUISTA TAILINGS IMPOUNDMENT

by

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Thesis

Presented to the Faculty of the Graduate School

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I would finally like to thank my family and friends who have helped me through these last two years in Austin. From New Jersey to Texas to Greece and back, I want to thank you all for supporting me and creating memories that I will never forget. It has been a big change moving away from everything I know and it has really meant a lot to have people along my side through this journey.

UNIVERSITY OF TEXAS - AUSTIN

Evaluation of Settlements at the Conquista Tailings Impoundment

by

Todd Michael Sheridan, MSE

The University of Texas at Austin, 2012

SUPERVISOR: Jorge G. Zornberg

CO-SUPERVISOR: Robert B. Gilbert

The following is a thesis presented on the history, subsurface characterization and settlement analysis of the Conquista Tailings Impoundment located in Karnes City, TX. This research draws information from readily available sources at TCEQ in Austin, Texas. Documents included in this report date back to the mid-1980s and can be as recent as 2011.

This thesis will focus on the eastern section of the Conquista Tailings Impoundment and will primarily observe and predict the settlement experienced in this portion of the site. The site has been analyzed using one-dimensional consolidation analysis, based on three (3) loading factors, and has been modeled using finite element analysis aided by the software PLAXIS.

The research has justified the magnitude of settlement that has occurred in the area of concern and has provided just reasoning for the events. Further investigations into the subsurface conditions in the eastern portion of the Conquista Tailings Impoundment will be needed to confirm and refine the analysis presented.

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## GLOSSARY

**Coefficient of Consolidation ($C_v$)** - The parameter used to describe the rate at which saturated clay or other soil undergoes consolidation when subjected to an increase in pressure.

**Compression Index ($C_c$)** – The parameter used to describe the rate at which the soil will compress due to loading.

**Consolidation** – "Consolidation is any process which involves decrease in water content of a saturated soil without replacement of water by air." – Karl Terzaghi

**Evapotransperative** - A term used to describe the sum of evaporation and plant transpiration from the Earth's surface to atmosphere.

**Hydraulic Conductivity** - The property that describes the ease with which water can move through pore spaces or fractures.

**Ore** - A type of rock that contains minerals with important elements including metals. The ores are extracted through mining; these are then refined to extract the valuable element(s).

**Perched Water Table** - A perched water table (or perched aquifer) is an aquifer that occurs above the regional water table.

**Piezometer** - A device used to measure static liquid pressure in a system by measuring the height to which a column of the liquid rises against gravity, or a device which measures the pressure (more precisely, the piezometric head) of groundwater at a specific point.

**Spigotted** – A method of spraying sludge, or waste, to induce sedimentation of materials. Courser material will settle first while finer particles will travel further.

**Decommission** - A general term for a formal process to remove something from active status.

**Tailings** - The materials left over after the process of separating the valuable fraction from the uneconomic fraction (gangue) of an ore. Also called mine dumps, slimes, tails, refuse, leach residue, or slickens.

**Tailing Ponds** - Areas of refused mining tailings where the water borne refuse material is pumped into a pond to allow the sedimentation (meaning separation) of solid particles from the water. The pond is generally impounded with a dam, and known as tailings impoundments or tailings dams.

# INTRODUCTION

This report presents an analysis of the settlements in the eastern section of the Conquista tailings impoundment located in Karnes County, TX (FIGURES 1 through 3). The site has historically experienced continued settlements in the eastern area of the site. These continued settlements represent a concern for the final closure of the site as they may create "ponding" zones, which in turn, may lead to continued maintenance. Unattended, continued settlements could compromise the ability of the cover system to function as an infiltration barrier. This report investigates the tailing material and subsurface conditions in order to identify the mechanisms leading to settlements and subsequently predict the future settlements. After an evaluation of historical documents, controlling load factors were identified that lead to settlements in the concerned area. Current and future settlements are thought to be induced by consolidation of the tailings material located beneath the clay cover system. That is, as water is squeezed out of the soil pores due to added weight, the material compresses causing settlement. Sources of loading include the placement of the original cover system, placement of additional cover soils for regrading of the cover, and continued lowering of the perched water table.

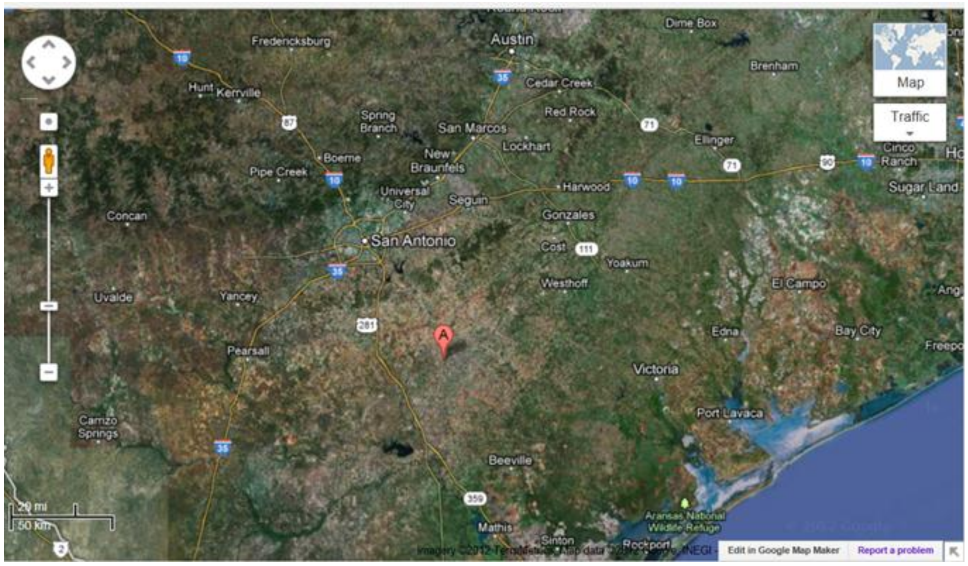


FIGURE 1 - Location of Conquista Tailings
Impoundment (Maps.Google.com)


FIGURE 2 - Location of Conquista Tailings
Impoundment (Maps.Google.com)

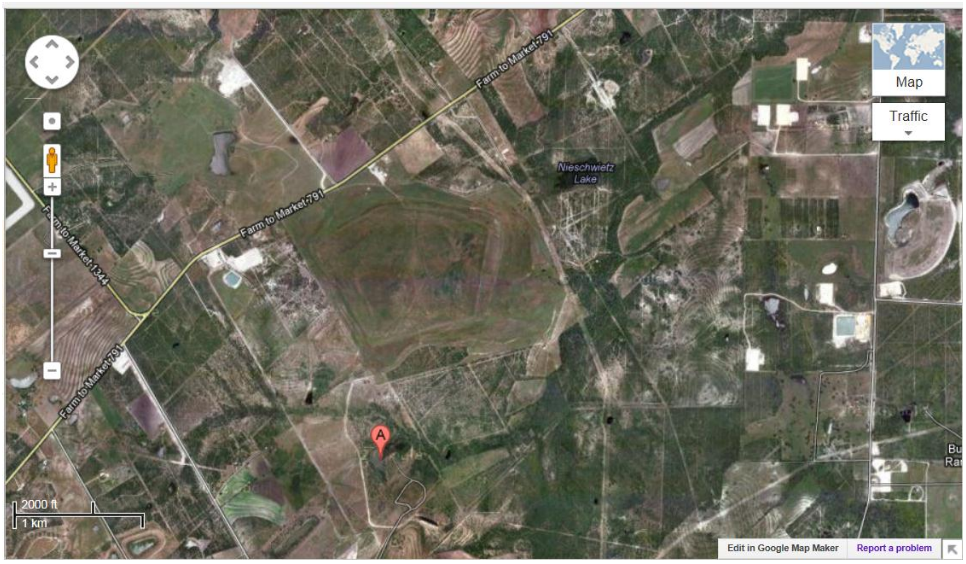


FIGURE 3 - Location of Conquista Tailings Impoundment (Maps.Google.com), Coordinates: (28.888, -98.099)

## OBJECTIVES

The objective of this project will be to analyze the settlement of a uranium tailings impoundment. The impoundment was initially closed with a cap in the 1980s. The closure cap was then upgraded in the 1990s due to problems caused by differential settlement of the tailings. Since that time, the tailings have continued to settle and cause maintenance problems.

The original set of objectives to complete consists of the following:

i. Review available reports and data concerning the properties of the tailings, the method of placement, the initial closure cap, the upgraded closure cap, and the settlement.
ii. Participate in a site meeting with personnel from TCEQ.
iii. Review previously submitted SIGMA/W, SEEP/W and FLAC Models
iv. Conduct a numerical simulation using a code agreed upon after discussion with TCEQ (e.g. FLAC, PLAXIS) to predict the settlement and calibrate it with the available data.
v. Use numerical simulation results to predict future settlement and cap performance.
vi. Produce a report summarizing the findings.

As will be discussed in this report, items iv and v of the original scope were expanded to incorporate one-dimensional settlement analyses. These analyses allowed one to gain insight into the properties and behavior of the subsurface materials.

## URANIUM MINING PROCESSES

Uranium mines can be found at the surface, open pit mining, or underground. The ore extracted from the mines is often of very low quality, between 0.1% and 0.2% uranium content. Therefore, a large amount of ore is needed to be mined to obtain an adequate amount of uranium (Wise-uranium.org).

Open pit mines are excavated from the surface to reach the uranium below grade. These mines were popular in the mid-1900s due to the ease of construction. Later, underground mines continued to increase in popularity. Two common mining techniques include heap leaching and in-situ leaching (Wise-uranium.org).

The heap leaching is a mining technique that can be used on excavated material when the uranium content is too low for the ore to be economically processed in a uranium mill. The leaching liquid, often sulfuric acid, is infused on the top of a pile of ore and penetrates down until it reaches a collection liner below. The liquid is then collected and pumped to a processing plant. There is always a risk that dust particles, radon gas, and leaching liquid may release into the environment when using this technique (Wise-uranium.org).

In-situ leaching (FIGURE 4) pumps leaching liquid, often ammonium-carbonate or sulfuric acid, through drill holes into underground uranium deposits. The leach fluid, which binds to the uranium, is then extracted and pumped out from below. This technique can only be used for uranium deposits located in an aquifer in permeable rock, confined by non-permeable rock. However, it is popular because it reduces the risk of injury and radon exposure to employees, is relatively inexpensive, and mitigates the need for large tailing piles. In-situ leaching presents the risk of leaching liquid beyond the uranium deposit, thus contaminating surrounding groundwater while also creating a condition that results in the impossibility of restoring natural conditions in the leaching zone when completed (Wise-uranium.org).

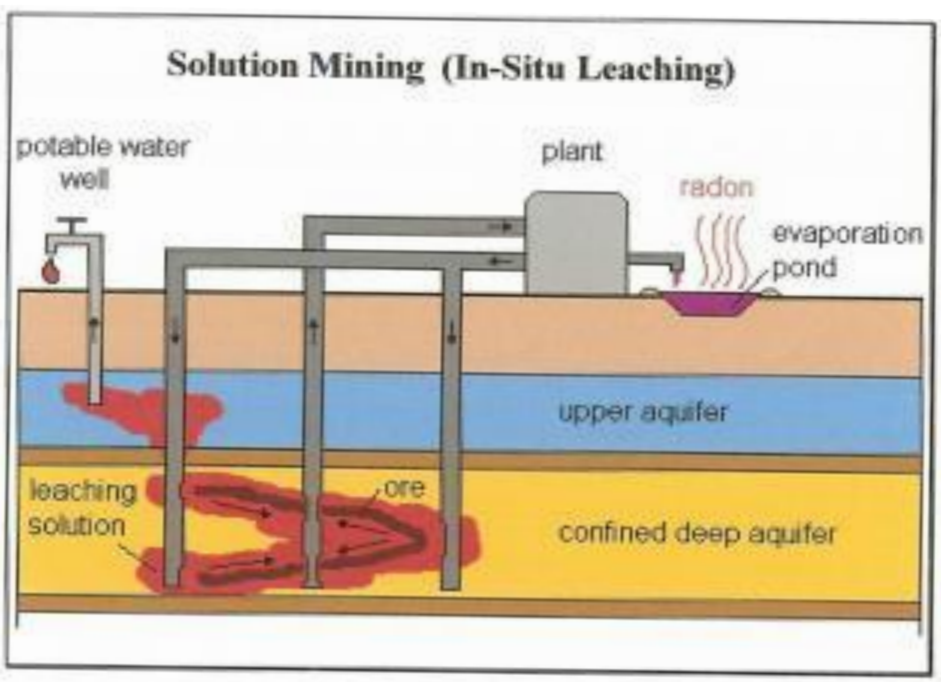


FIGURE 4 - In-situ Leaching Process (Uraniuminfo.org)

# CONTAINMENT OF URANIUM TAILINGS

The uranium bearing material from open pit or underground mines is leached in a uranium mill processing plant in order to extract the uranium present. These mills are usually located on, or near, the site to reduce transportation costs and typically use sulfuric acid to extract the contents. Along with uranium, the leaching agent extracts various constituents from the ore such as vanadium, selenium, iron, lead and arsenic. The final product, often referred to as "yellow cake," contains $U_3O_8$ and some impurities. After the completion of a mining site, the mill and equipment used may contain large amounts of radioactively contaminated material. This material must be disposed of in a secure and proper manner. Commonly, tailing impoundments are constructed to contain the waste produced (Wise-uranium.org).

Uranium mill tailings are commonly disposed as sludge in specialty ponds or piles. The amount of sludge produced is about the same as the ore milled (with a uranium content of 0.5%, 99.5% of the material is waste). The concerns associated with the sludge lie in the radioactivity of the material. Approximately 85% of the initial radioactivity remains in the sludge after processing. In addition to this, heavy metals and other contaminants used during the milling process exist in the sludge. The waste produced is impounded at specific sites to meet predetermined standards set by the Environmental Protection Agency (EPA) and the Nuclear Regulatory Commission (NRC) (Wise-uranium.org).

The tailing deposits must meet the legal requirements as defined by the EPA and the NRC. These regulations define the maximum contaminant concentrations for soils, admissible radon release (20 pCi/m$^2$-sec) and life expectancy for the impoundment (200-1000 years). This demand of life expectancy must assure a safe disposal for the duration without active maintenance. If these conditions are not met, the tailings must be relocated (Wise-uranium.org).

FIGURE 5 depicts some of the potential hazards.

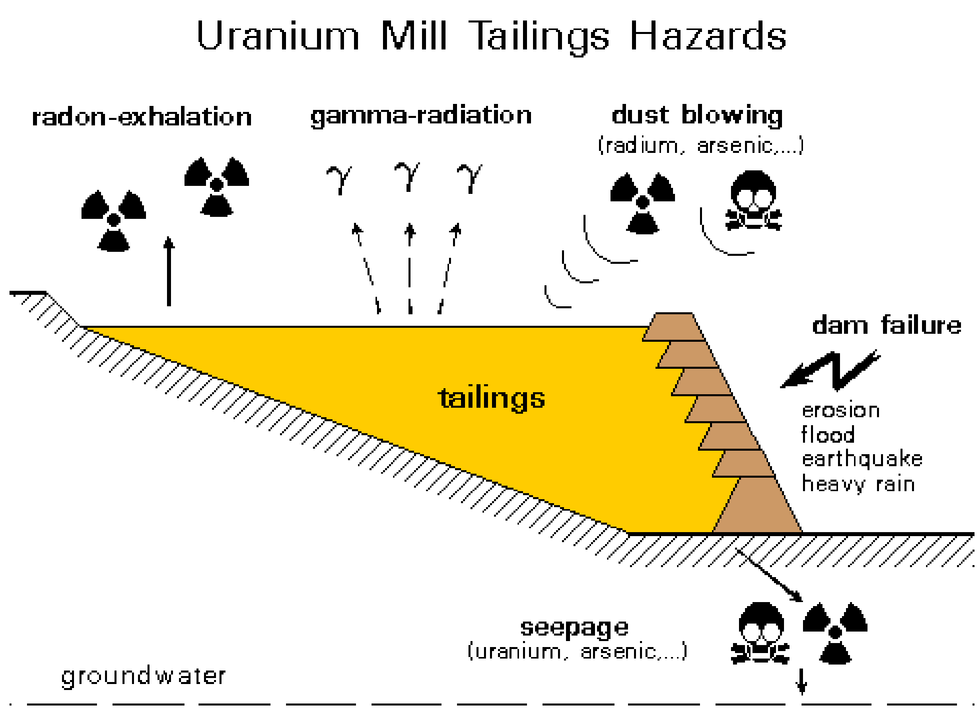


Figure 5 - Potential Hazards (AntiNuclear.net)

## HISTORY OF URANIUM MINING

Although the use and properties of uranium were not known at the time, minerals, acknowledged as pitchblende, were discovered as early as 1565. Pitchblende was extracted from the ground in a yellowish powder form; however, throughout the ages this powder was misidentified as sulfur. The first deliberate mining process of uranium ore took place in the 19th century, in the present day Czech Republic. The first process was intended to extract the ore for use as radium, which is the decay product of uranium. With such little known about the element at the time, many deaths came about from radiation poisoning. The early use of uranium ore was primarily luminous paint for watch dials and other instruments, as well as some health-related applications. As we now know, the health-related applications may have produced harmful rather than beneficial outcomes (Cna.ca).

Uranium ore deposits were discovered in the United States in 1871 within the gold mines of Colorado. Pre-World War II, the majority of our uranium ore deposits were mined in the vanadium deposits of the Colorado Plateau, between Utah and Colorado. During the war, and the construction of the Atomic Bomb, the mining process moved to the American Southwest. Specifically, Arizona and New Mexico provided much of the supply for the Manhattan Project.

Governmental agencies needed to effectively conceal the purchase of uranium for obvious reasons; therefore, they instead purchased vanadium, which was known to have traces of uranium that could be extracted for use (Cna.ca; World-nuclear.org).

Currently, Kazakhstan, Canada, and Australia are the leading producers of Uranium. Uranium is traded in the commodities market as $U_3O_8$ at a price of \$52/lb (February 2012), but this has not always been the case. In the 1980s, the price dropped down to \$7/lb., which caused many mining operations to declare bankruptcy and shut down, leaving their tailings and radioactive deposits behind (World-nuclear.org).

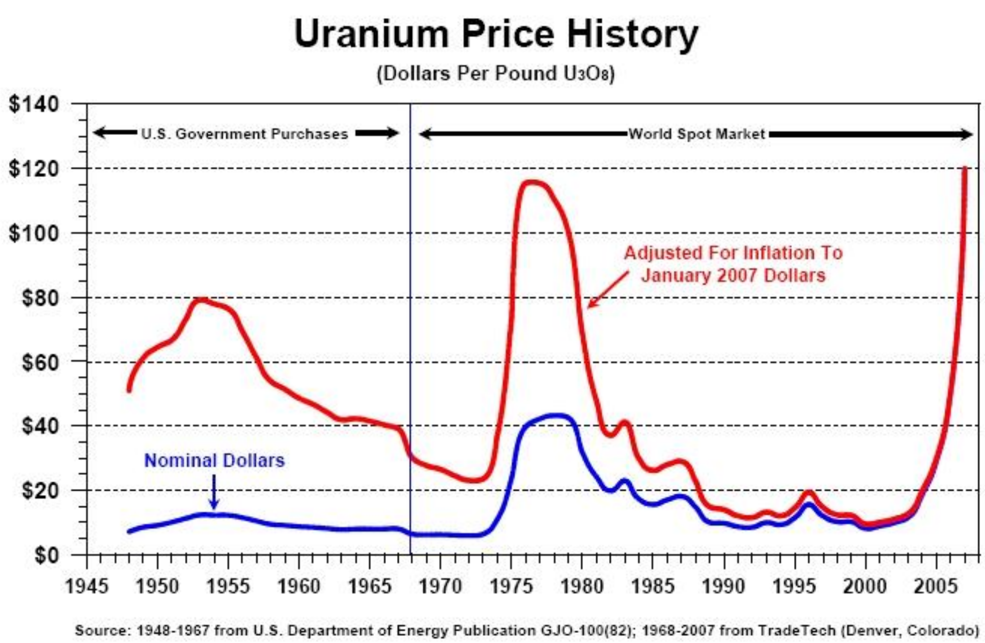


FIGURE 6 - Price of Uranium through History
(SeekingAlphas.com)

## URANIUM MINING IN TEXAS

Mining for Uranium in Texas began in the mid-1950s. The deposits were found using aerial detection for radioactive material. To the miners' surprise, the ore grade uranium was found in the crustal layer and was relatively easy to access. The material was located in a farmland in Karnes County, TX, creating a "gold rush" effect for farmers and oil tycoons. Most notably, Susquehanna Western, Inc. was at the forefront of this exploratory expedition (Uraniuminfo.org).

The process of mining began as an unregulated open-pit mining operation that resulted in companies dumping tons of hazardous, radioactive metals in the south-central Texas area, outside San Antonio. The most notable projects in this area were at the Conoco/Conquista site in Karnes County, at the Chevron site in Panna Maria, also in Karnes County, and at Exxon's Ray Point site in Live Oak County. Consequentially, these sites produced excess waste. Uranium tailings result from disposal of waste material from a conventional uranium mill, which can contain radioactive byproducts and heavy metals. Tailings are described to include discrete surface waste resulting from the uranium solution extraction processes. These processes are comprised of techniques such as in-situ recovery, heap leach, and ion-exchange. Byproduct material does not include underground ore bodies depleted by solution extraction. The waste from these solution extraction facilities is transported to a mill tailings impoundment for disposal (Uraniuminfo.org).

By the mid-2000s, there were uranium operations in eighteen (18) counties in southwest Texas with forty (40) strip-mines permitting coverings (over 31,000 acres), which included four (4) uranium tailings ponds. Eighty (80) in-situ mining sites, with over 20,000 surface wells, were licensed. These sites use surface wells to extract the element with the use of solvents. Thirty-two (32) deep well injection sites were permitted for use of disposal of radioactive waste into deep aquifers (Uraniuminfo.org).

# SITE HISTORY

The sites in south-central Texas that contained uranium were located on Eocene Sandstone deposits. Continental Oil Company operated a mill site on these deposits in Falls City, TX from September 1971 until January 1982, where it was then transferred to Conoco. The operations were conducted to recover uranium from the sandstone using several open-pit mines in the surrounding area. The Falls City Conquista site is located approximately eight miles southwest of Falls City, TX in Karnes County, a 614-acre tract of land in which the pentagon-shaped tailings impoundment covers 243 acres (Waste, Water & Land, 1994).

The mill produced approximately 8.75 million tons of uranium ore at an average concentration of 0.10 percent and manufactured more than 2000 tons of uranium oxide ($U_3O_8$) for the U.S. Atomic Energy Commission. The mill used a conventional sulfuric acid leach and solvent extraction process to recover the $U_3O_8$ from the ore from the sandstone that was milled. The tailings produced from this operation amounted to more than 3.1 million tons of waste, which came in forms of sand and slime fractions, as well as liquid waste generated from the process. The waste disposed in the ponds also consisted of milling materials and equipment, treated sanitary waste, laboratory waste, and runoff from the ore pad and mill area. This waste was disposed across the site and impounded in unlined settling ponds. These "tailings ponds" reached depths of forty (40) feet and were located above a naturally occurring clay aquitard. The ponds were then evaporated and the remaining land was enclosed with a vegetated cover system. Due to differential settlement, the initial closure cap was upgraded in the 1990s (Waste, Water & Land, 1994).

The original ground surface elevations ranged from 360 feet above mean sea level at the eastern side, to 420 feet above mean sea level at the southwestern corner. When initially constructed in 1971, the impoundment made use of the natural drainage path of Conquista Creek, which was confined by embankments only on the eastern and northern sides and high grounds of the western and southwestern locations. The embankments were constructed out of the existing Dubose Member clay found within the impoundment and at select borrow areas. The tailings were spigotted from the outer edges of the embankments to create "tailing beaches" on the perimeter and "slime ponds" in the central areas. Ponded water was then pumped out for re-use in the mill process (Waste, Water & Land, 1994).

The embankments rose to a maximum height of forty-five (45) feet, on the eastern side, with the majority rising no more than ten (10) to fifteen (15) feet. In 1979 and 1981, the embankments were then raised to an elevation of 416 and 436 feet above mean sea level, respectively. The final embankment heights ranged from sixteen (16) to seventy (70) feet with a 3:1 downstream slope (outside) to the natural ground and a 2:1 slope upstream (inside). FIGURE 7 shows a free hand sketch depicting the subsurface conditions at the site (Waste, Water & Land, 1994).

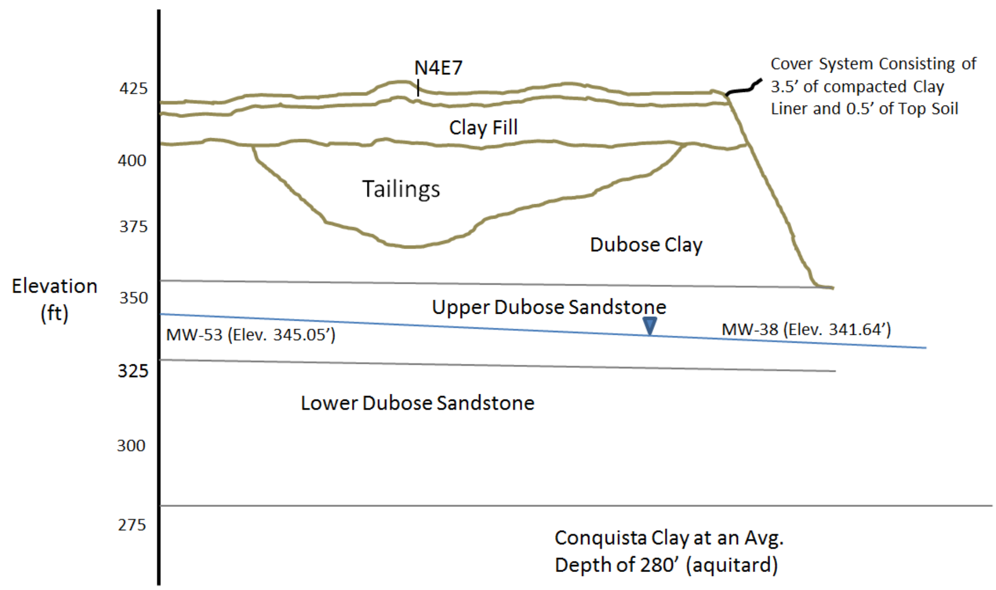


FIGURE 7 – Cross Section of Conquista Tailings Impoundment

## EMBANKMENT CONSTRUCTION AND TAILINGS DEPOSITION

The pentagon-shaped impoundment covers an area of roughly 250 acres that is enclosed by surrounding embankments. The initial ground surface elevation in 1979 ranged from 360 feet at the eastern confinement to over 420 feet at the southwestern corner. The embankments were constructed on a naturally dry area of Conquista Creek with a 2.5:1 upstream slope and a 3:1 downstream slope. Crest widths varied from fifteen (15) to twenty (20) feet. The embankments were constructed of borrow material from the southwestern area of the site. Up to twenty (20) feet of homogeneous compacted clay was excavated. The eastern embankment rose to a maximum height of forty-five (45) feet with the majority of the section being less than ten (10) to fifteen (15) feet (Tetra Tech, Inc., 2011).

In 1981, the embankments were raised almost twenty (20) feet to a final elevation of 436 feet. The height increase of the embankments was constructed using a centerline method with a clay core and a shell composed of random fill. The downstream side of the embankment remained at a constant 3:1 slope, while the upstream face was constructed with a 2:1 slope and a crest width of approximately twenty (20) feet (Waste, Water & Land, 1994).

The embankments were constructed with seepage collection systems built into the downstream toe of the embankments. This system drained to sumps located at the low points across the embankments. An interceptor ditch was created to collect runoff from the small upstream drainage area. The ditches allowed the water to be diverted around the pond and into the natural downstream drainage. The collection system discharges through solid pipes into sumps located outside the embankment perimeter. The discharge is then pumped back into the tailings pond (Tetra Tech, Inc., 2011).

The tailings were discharged along the northern and eastern sides of the impoundment using a sub-aerial method of spigotting around the entire perimeter. This method of discharge kept the free water surfaces away from the embankments and resulted in the formation sand tailings beaches along the embankments. The tailings beach reached a maximum elevation of 424 feet on the upstream face of the embankment. The downstream slopes were seeded with Costal Bermuda grass to create a vegetative cover to reduce erosion (Waste, Water & Land, 1994).

## MILL SITE DECOMMISSIONING

The initial mill site decommissioning began at the end of the secondary recovery in October of 1982 and was completed by the end of 1984. In 1983, the mill site equipment was dismantled and what could be used again was sold. Materials and equipment that could not be sold were disposed of into the tailing ponds. Before decontamination took place, a gamma survey was conducted and the contaminated areas were marked. Excavation of these areas was conducted using a backhoe and scrapper, this excess material was then buried in the impoundment. After the decontamination process was complete, the western two-thirds (2/3) of the impoundment was covered with approximately five (5) feet of clean fill. After a second gamma survey confirmed the area was decontaminated, a layer of topsoil was placed on top and seeded with native grasses. FIGURE 8 depicts a plan view of the Conquista Impoundment (Tetra Tech, Inc., 2011).

Tailings pond water was managed by pumping the residual pond water to the eastern section of the impoundment prior to covering this section. At this time, the eastern section of the impoundment was still open as pond water and runoff were contained in these tailings. At the closing of the reclamation work in 1985, approximately 160 gallons of pond water covered the eastern portion of the impoundment. This water was evaporated initially by spraying along the "tailing beaches" to provide evaporation from the wetted surfaces. Later stages of the project led to the construction of smaller evaporation cells to facilitate the process prior to fill placement Tetra Tech, Inc., 2011).

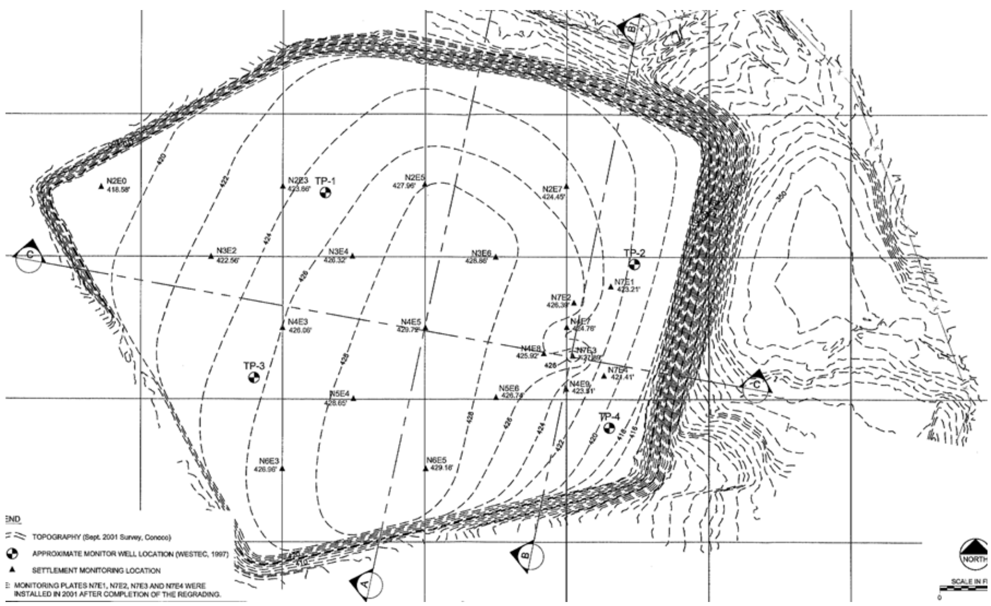


FIGURE 8 – Plan View of Conquista Tailings Impoundment (Conoco Phillips, 2011)

Due to the prospect of differential settlement, the reclamation plan was revised in 1991. The revised plan consisted of a domed surface sloping to the west at a 0.5 percent slope and sloping to the east at a 1.0 percent slope. The downstream embankment faces were reduced to a 5:1 slope. This configuration was designed to minimize the volume of earthwork needed while meeting the required regulation standards set by Texas Regulation for Control of Radon (TRCR). The final surface of the impoundment was constructed by a regrading of the tailings, as well as random fill placement. FIGURE 9 shows the progression of decommissioning (Tetra Tech, Inc., 2011).

Since the tailings beneath the western section of the impoundment had been pre-loaded with a minimum of five (5) feet of random fill it was allowed to consolidate for four (4) years prior to the closure of the eastern portion. This

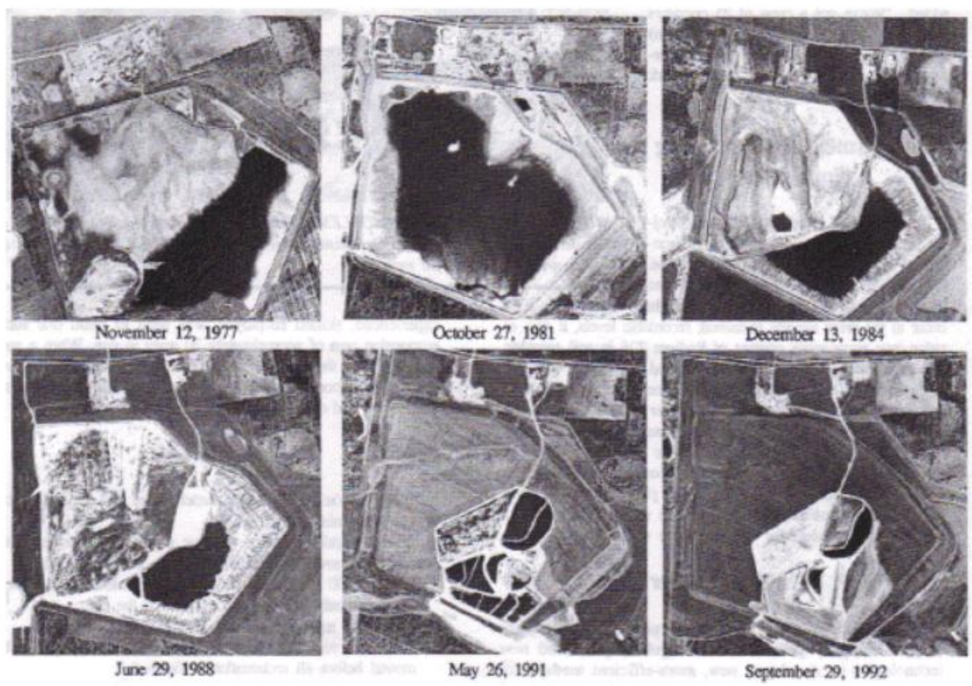


FIGURE 9 – Progression of Impoundment Decommissioning (News Article - unreferenced)

allowed conventional earthmoving equipment to be used in this area. The tailings along the perimeter of the eastern portion of the impoundment did not have the same pre-loading and consolidation history, therefore specialty equipment, such as small dozers and high-flotation pull scrapers, was used. This allowed the regrading work to take place within one (1) foot of the saturated zone of the tailings. Following the regrading of the tailings, a geogrid was laid in order to allow for uncomplicated machine operation when placing the random fill. The random fill placed above the tailings varied from five (5) to fifteen (15) feet with an average depth of ten (10) feet (Tetra Tech, Inc., 2011).

Additionally, an engineered cover was designed for placement on top of the regarded surface. The cover consisted of a 3.5-foot thick compacted clay cover and 0.5 feet of topsoil. The compacted clay layer allowed the engineered cover to reduce the average rate of radon emanation to the regulated value of 20 $pCi/m^2$-sec and a hydraulic conductivity of less than $10^{-7}$ cm/sec. The low hydraulic conductivity helped mitigate issues relating to ground water control. The final closure plan included a vegetative cover, which required gentle slopes and uniform surfaces, to meet the TRCR regulations for erosion stability control (Waste, Water & Land, 1994).

The primary material used for the cover system was collected from the site at three (3) locations; borrow areas from the southwest, southeast, and north side of the impoundment. The Dubose clay found in these areas was selected based on permeability testing, radon attenuation testing and modeling, and dispersivity testing. The material from the southwest borrow area was also used in the initial reclamation plan in 1984. Materials that did not meet the specifications were used as random fill underneath the engineered cover in order to meet the desired slopes (Tetra Tech, Inc., 2011).

## COVER SYSTEM

Initial Cover System (1984):

At the time of decommission, the equipment and materials from the mill that could not be decontaminated or salvaged were buried in the tailings impound. The initial reclamation plan of 1984 consisted of covering the western part of the impoundment with borrow material from the southwestern corner of the site. The thickness of the fill material was approximately five to ten feet in depth. It was constructed by pushing fill from jetties built across the impoundment (Waste, Water & Land, Inc., 1987).

Final Cover System (1992):

The final cover system was designed as an attempt to mitigate differential settlement of the previously designed system and meet EPA and NRC standards. This final cover consisted of three and a half (3.5) feet of compacted clay to create a radon and water barrier between the surface air and the contaminated material. A final six (6) inches of topsoil was placed on top to create a vegetative surface (Steffen Robertson and Kirsten, 2000).

The NRC Guidelines for uranium tailings impoundments are documented in 10 CFR 40, Appendix A (1987). This states that the run-off from the surface is not allowed to "pond". The design of the domed surface created proper run-off channels for the water to escape, but differential settlement throughout the eastern portion has created a great concern for the existing cover.

The NRC stipulates that the site must have isolations, or control, of radiologic hazards. The containment is to be effective for 1000 years or, in any case, for at least 200 years, and will limit the release of radon-222 to the atmosphere, which should not exceed 20 $pCi/m^2$-sec. These standards have been met by the cover system installed. Since the deposition of the waste below grade is not possible due to near-surface groundwater, the embankment-surrounded, above-grade impoundment meets standards of requirement.

Finally, the configuration of the confinement and domed surface creates an adequate assessment for minimizing upstream catchment. The vegetative cover installed satisfies the NRC's requirement for wind erosion protection and an established vegetative cover. The impoundment is located in an inactive fault zone, but has still been designed for site seismicity. The final requirement requests for features that promote deposition of sediments. This requirement has been fulfilled by the process of spigotting the slimes to create tailing beaches.

FIGURE 10 depicts the cross section of the final cover system design.

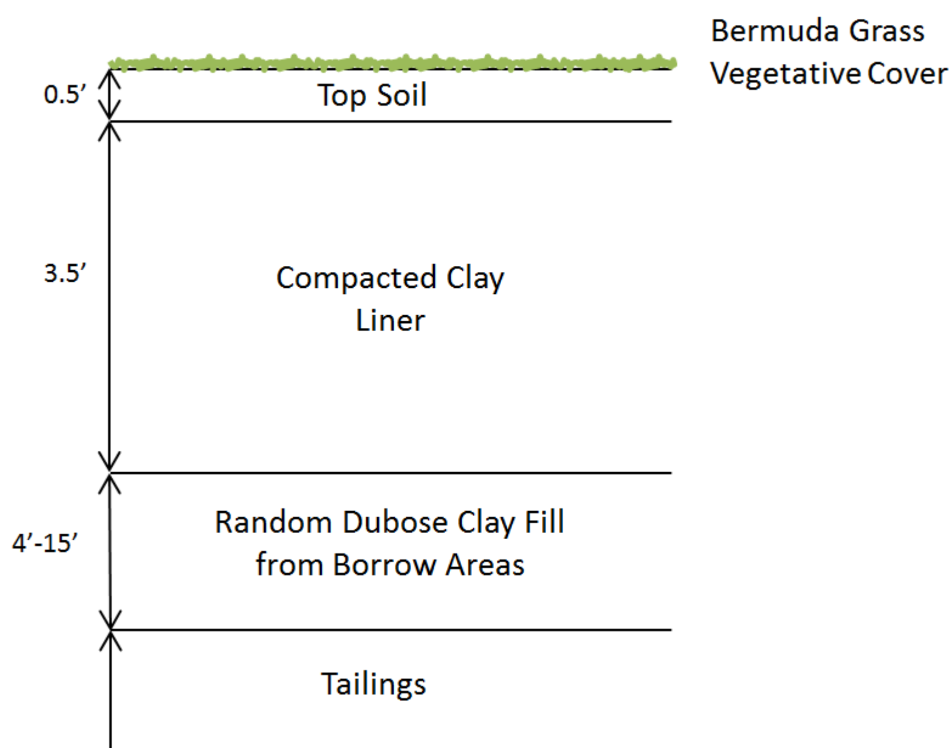


FIGURE 10 – Cross Section of Final Cover

SETTLEMENT DATA

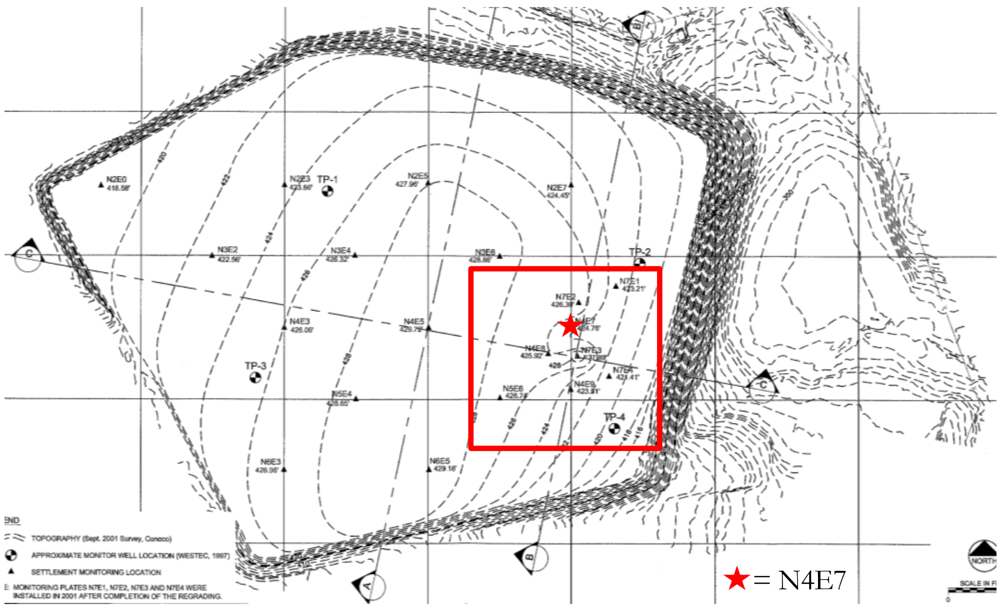


FIGURE 11 – Area of Concern (Conoco Phillips, 2011)

Beginning in 1993, after the final cover system was installed, settlement data was collected in the field. FIGURE 12 shows ground surface elevations (AMSL) versus time at the locations of interest, FIGURE 11.

As well as depicting the ground surface elevations, FIGURE 12 shows the additional lifts added in the attempt to mitigate the settlement that accumulated and bring the ground elevation back to grade. It can be seen that in 2001 a lift of five (5) to ten (10) feet was placed in the area of the settlement monument locations. The lift was added to fill in the areas that amassed the most settlement throughout the previous ten (10) years. The added load created by the weight of the soil caused the consolidation process to continue, and therefore increased ultimate settlement (Tetra Tech, Inc., 2004).

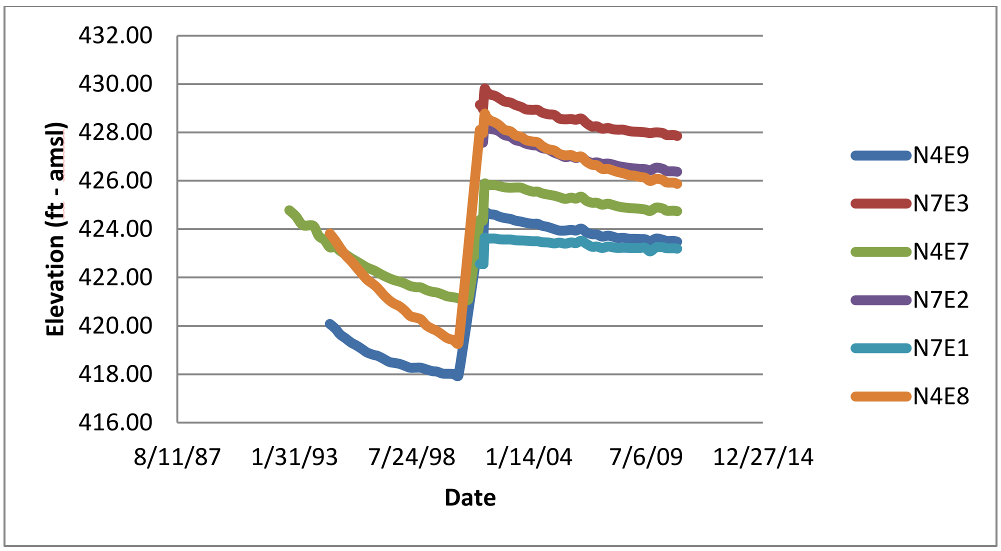


FIGURE 12 – Ground Surface Elevations

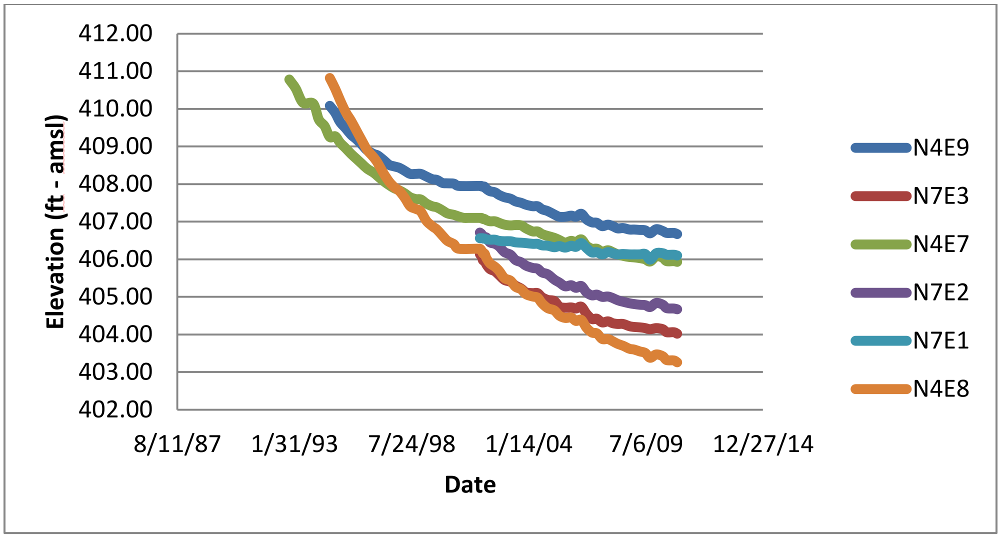


FIGURE 13 – Top of Tailings Elevations

This additional lift of fill material added to the eastern portion will be considered the second loading factor. By removing the depth of the cover system and the second lift of additional fill, the settlement data can be reconstructed to determine the elevation of the tailings surface. FIGURE 13 is a plot of the elevation of the tailings surface (Tetra Tech, Inc., 2004).

For analysis settlement monument N4E7 will be used as a comparison to calculated settlements. N4E7 is located directly above the thickest section of tailings. Tailings below N4E7 reach a thickness between 35-40 feet and will generate the most settlement (Tetra Tech, Inc., 2004).

## GROUNDWATER CONDITIONS

Throughout the site there have been sixteen (16) piezometers installed along with twenty-six (26) monitoring wells to observe the water level around the perimeter of the site. These piezometers and monitoring wells have been installed to note the water levels within the Dubose Sands and Deweesville Sands. In addition to these piezometers and monitoring wells, four (4) test pit wells were installed with monitoring well to monitor the height of the water table in the tailing material. Two (2) test pits, TP-1 and TP-3, have been installed in the western portion of the impoundment and two (2), TP-2 and TP-4, in the eastern portion (Tetra Tech, Inc., 2011).

The elevation of the perched water table in the eastern portion of tailings is monitored by TP-2 and TP-4, with screen intervals of 24.2 - 34.2 feet and 24.9 - 34.9 feet below the ground surface, respectively. These wells have steadily decreased since installation. TP-2, which is located in the northern area of the eastern tailings has decreased from a maximum level of 404 feet above mean sea level to 394.25 feet above mean sea level. TP-4, located in the southern area of the eastern tailings has followed suit and decreased from a maximum level of 403.5 feet above mean sea level to 394.25 feet above mean sea level. FIGURE 14 shows the ground water elevation within the eastern tailings, TP-2 and TP-4 (Tetra Tech, Inc., 2011).

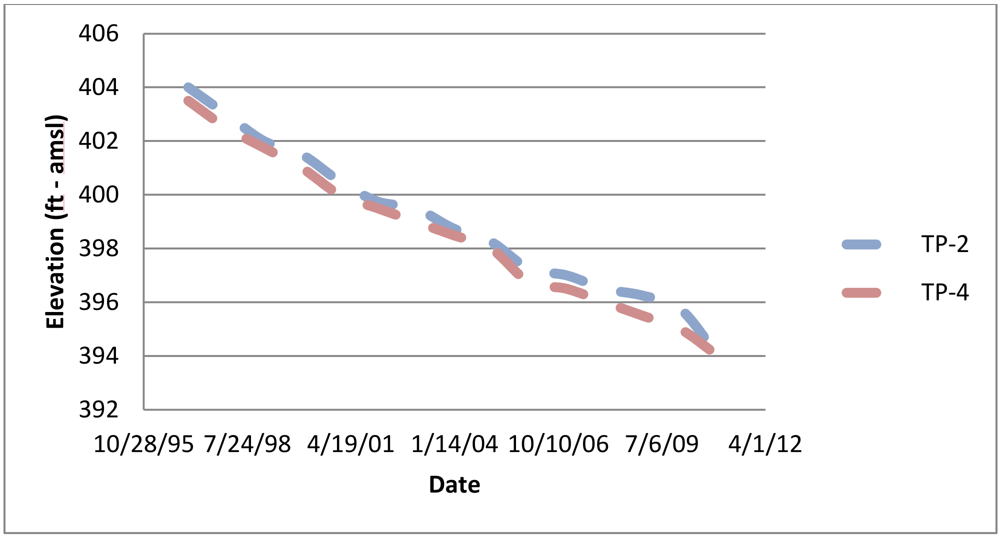


FIGURE 14 – Perched Water Table Elevations
Within Tailings

As the elevation of the perched water table within the tailings is lowered, the buoyancy of the soil is reduced and the additional weight created by this effect is carried by the soil below. This loading effect is the final component that will contribute to the settlement of the tailing material. As the water table lowers, the weight and pressure acting vertically on the soil increases, which will create an increase in settlement due to the consolidation of the material (Tetra Tech, Inc., 2011). An additional assessment has been performed in case additional fill will be needed to bring the surface elevation back to the original grade of 422 feet above mean sea level. For the consolidation analysis, three (3) loading sources have been identified to affect the tailing material and will be evaluated in the following order:

1. The continued lowering of the water table
2. The installation of the cover system in 1993
3. The additional fill added to surface in 2001 and 2014

# LABORATORY DATA

Since the conception of the Conquista Tailings Impoundment, testing has been conducted on the material existing around, below, and within the site confines. The main laboratory report compiled is by Waste, Water & Land, Inc.(WW&L), which is dated 1986. Various tests, which can be found in the WW&L report, were conducted on the relevant soils in the area of the tailings. Within these tests, the tailings were also sampled. The problem with the data presented in the report mentioned above is that the tests were conducted on samples from the western portion of the impoundment, over two and a half decades ago. The tailings contained in the western portion will most likely have different consistencies and properties, in addition to these regions having changed over the past couple decades. By defining the properties of eastern tailings using data from the western tailings, many uncertainties are presented, as well as additional room for error.

Although the reports presented data from the western portion of the site, the initial void ratio ($e_0 = 2.5$) and unit weight of the tailings ($\Upsilon = 83$ pcf) were used when defining the characteristics of the eastern portion. These characteristics seem reasonable to use because the tailings were removed using the same method of extraction from the same location, and were initially deposited using similar methods (Waste, Water & Land, Inc., 1986).

Relevant information, for use in other parameters, could not be found for tests conducted in the eastern portion of the tailings. Parameters, such as the consolidation coefficient or the compressibility coefficient, can lead to large variations in final settlements if wrong values are assigned. Further tests and refinement of data need to be conducted within the eastern tailings in order to obtain more accurate analysis.

## MAY 29th, 2012 SITE VISIT

On May 29th, 2012, Todd Sheridan, Dr. Zornberg (University of Texas – Austin), and Michael Pimentel (TCEQ) visited with Ernest King, the site manager, at the impoundment in Karnes County, TX. During the site visit the settlement monuments were located and the local conditions of the site were observed. While walking the eastern portion of the site, it was easily visible that large cracks were forming at the surface. The cracks that were observed (FIGURE 15) ranged from 5-14 inches in length and between 2-4 inches in thickness. One crack was seen to extend more than twelve (12) inches below the ground surface. These cracks could not be found on the western area of the impoundment. These cracks could lead to problems affecting the integrity and structure of the liner.

FIGURE 15 – Picture of Soil Cracks in Eastern Portion (Picture From Site Visit)

# Chapter IV: One-Dimensional Consolidation Analysis

The continued lowering of the perched water table, in accordance with the settlements observed, led to the belief that the settlements observed derived from a consolidation condition. To consider consolidation as the primary factor contributing to the settlements observed, a one-dimensional consolidation analysis will be conducted with a linear e-log p curve, a constant $C_c$ value and an initial void ratio under normally consolidated conditions. The void ratio will vary with time as the subsurface compresses and is a function of the compressibility of the material. The initial void ratio used is 2.5. Normally consolidated conditions are assumed because the only initial load the tailings have experienced is the loading of their own weight. The assumptions were used to simplify the analysis based on the lack of initial parameters presented in the eastern portion. The limited initial parameters used, $e_0$ and $\gamma_{tailings}$, were taken from the Waste, Water & Land report conducted on the western sections.

It must be noted that assuming a constant $C_c$ based on the linear e-log p curve, will overestimate the settlement reported. This overestimation occurs due to the fact that as the layer of tailings settle and consolidate, the coefficient of compressibility will decrease as the layer densifies. The consolidation analysis conducted applied two (2) methods of calculations and a combined approach.

## APPROACH 1: IMMEDIATE SETTLEMENT DUE TO LOADING WITH COVER SOILS

Approach 1 began by defining the compression index ($C_c$) based on the settlements due to immediate loading of the cover system and the lowering of the water table. When the compression index is varied and matched against the corresponding data from the settlement monuments, an adequate compression index for analysis can be back-calculated. In order for the procedure to be accurate, it must be assumed that $C_c$ is constant with time and that the excess pore pressures which are generated by the lowering of the water table will dissipate at the same rate as the water level drop. FIGURE 16 shows how the settlement will vary with a changing $C_c$. FIGURE 17A compares the selected value of $C_c$ = 0.5 with the actual settlement monument data from N4E7. FIGURE 17B has been implemented into the report to show the effects of an additional six (6) feet of fill.

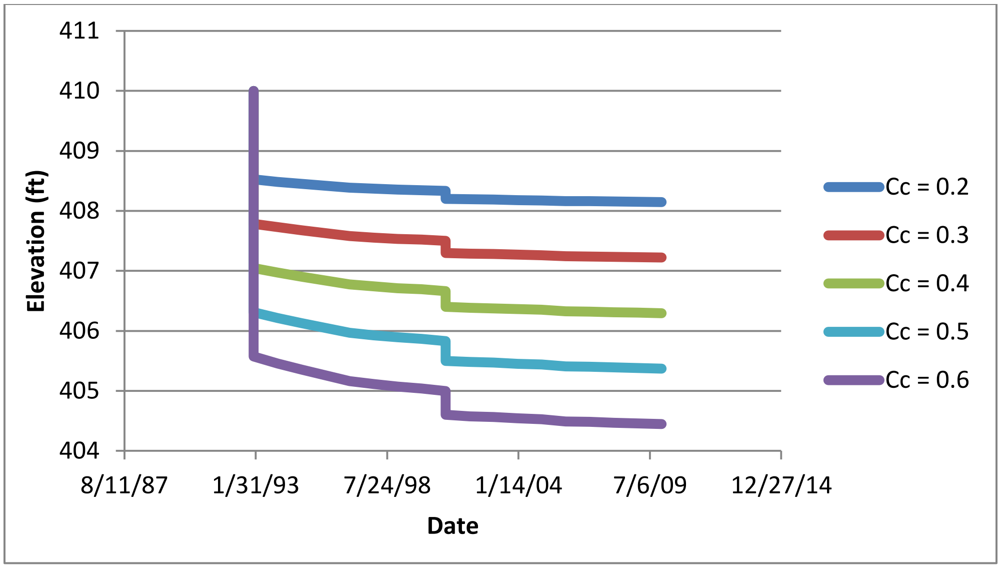


FiGURE 16 - Settlements Using Approach 1

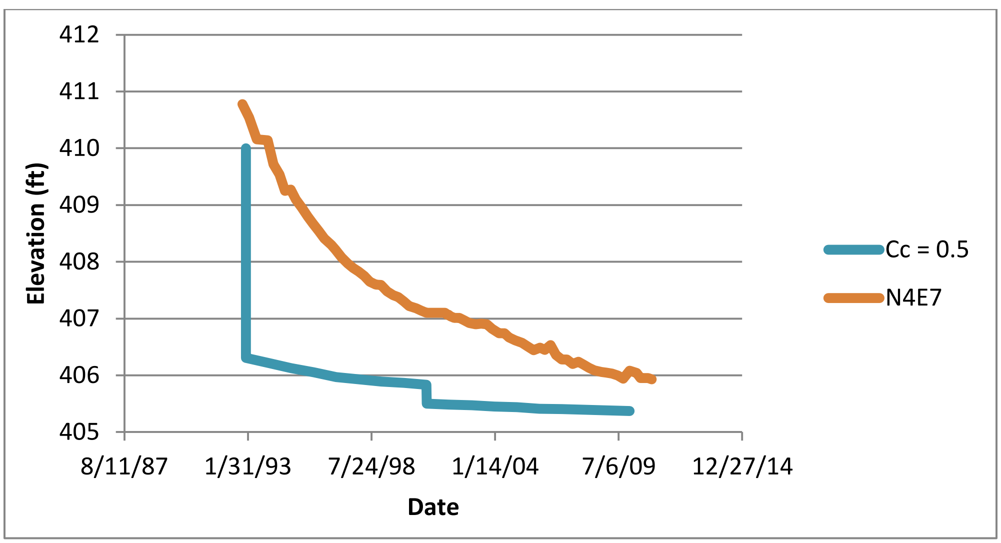


FIGURE 17A - Approach 1 ($C_c$=0.5) with
N4E7 Settlement Monument Data

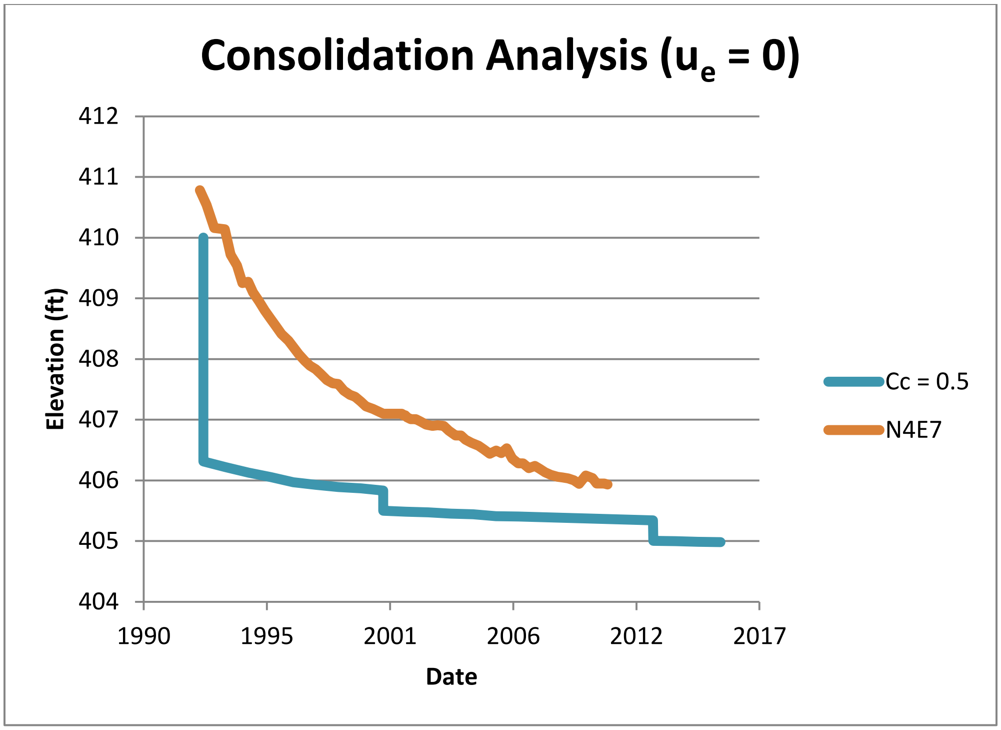


FIGURE 17B - Approach 1 ($C_c$=0.5) with additional lift of fill and N4E7 Settlement Monument Data

The vertical lines shown on the graph are directly related to the immediate loading of the cover system in 1994 and the additional lift added in 2001. When these settlements are removed, the settlement data remaining is only due to the lowering of the water table, as shown in FIGURE 18. As expected, the settlements predicted with Approach 1 exceed the actual monitored settlements at any given time. This can be attributed to the assumption that the excess water pressures will dissipate at the same rate at the reduction in ground water elevation.

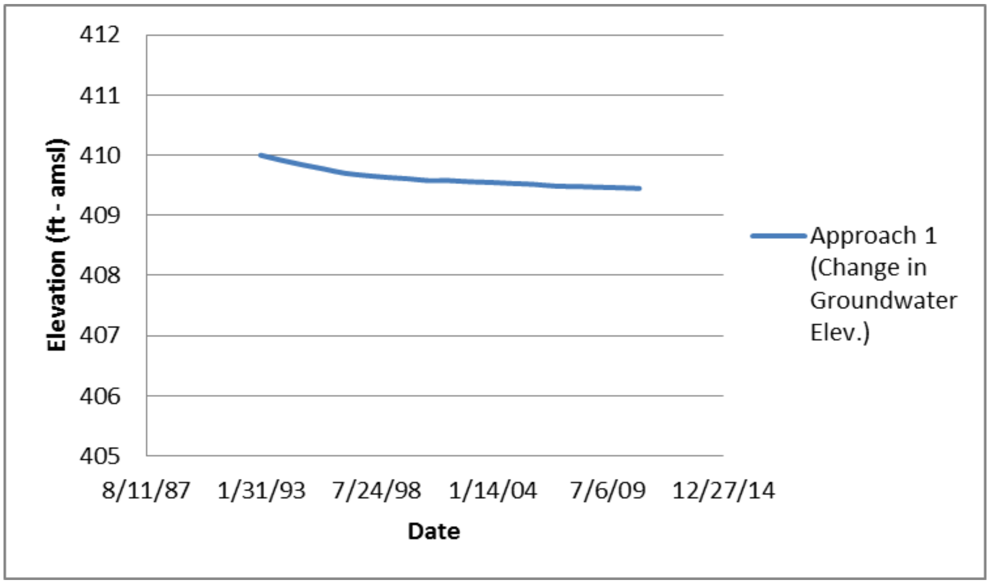


FIGURE 18 - Approach 1 Settlement due to Change in Water Table Elevation

## APPROACH 2: TIME-DEPENDENT SETTLEMENTS DUE TO LOADING WITH COVER SOILS

Approach 2 takes into account the time history of the settlements by accounting for a consolidation coefficient ($c_v$). To begin this method, the ultimate settlement under the load applied was initially defined using $C_c$ and commonly used geotechnical applications. This method assumes that the water table will remain at a constant height and the settlement that occurs will be due, solely, to the loading of the cover system and additional lift applied at the surface. After the ultimate settlement has been defined, the percent of consolidation must be defined from $c_v$ ($c_v$ = 120 ft$^2$/day) and the time of consolidation. The percent of consolidation allows for the understanding of how much consolidation has occurred and how much has still yet to transpire. FIGURE 19A shows the effect of settlement due to the cover system (First Cover) and the additional lift in 2001 (Second Cover). By the time the addition of the second cover was placed, the settlement caused by the first cover reached a maximum. The addition of the second cover created a greater surface load which induced further settlement. FIGURE 19B has been added to depict the effects of a third and final lift of material, with a thickness of six (6) feet, that will bring the elevation of the surface back to original grade. FIGURE 20 plots the settlement data from Approach 2 against the settlement monument data recorded on site.

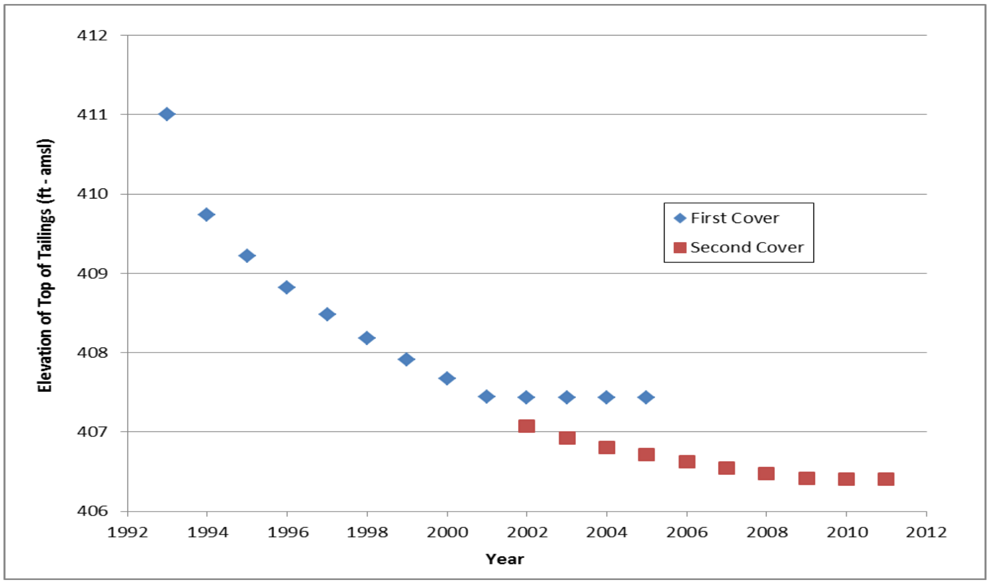


FIGURE 19A - Settlements Using Approach 2

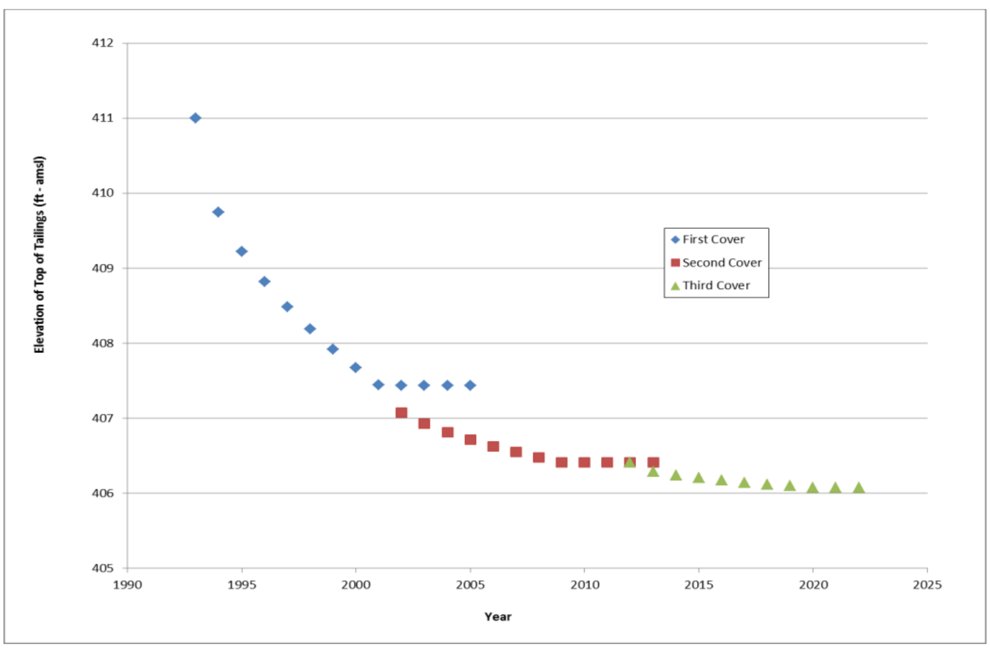


FIGURE 19B - Settlements Using Approach 2
with a third lift of fill

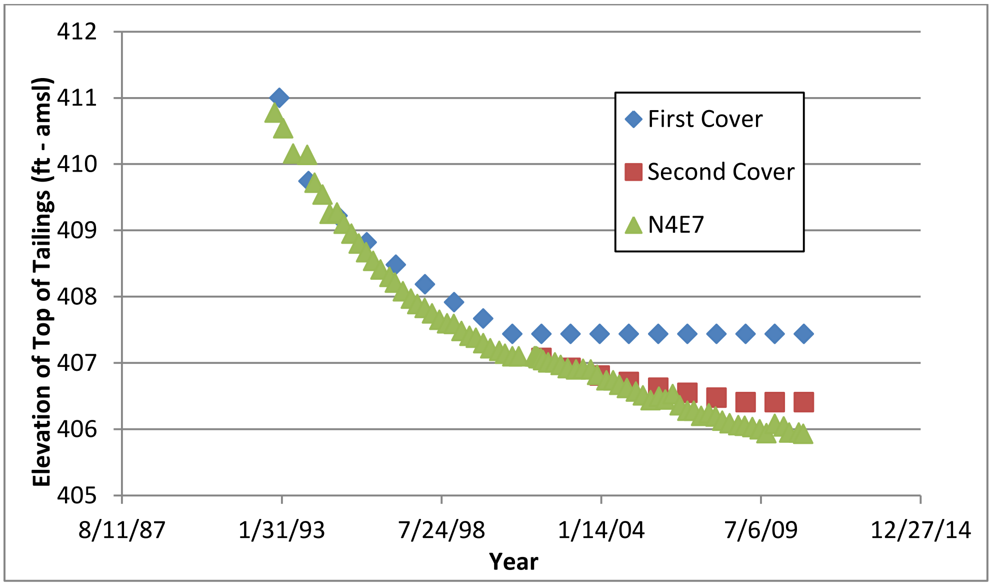


FIGURE 20 - Approach 2 ($C_v$=120 ft$^2$/day) with
N4E7 Settlement Monument Data

## APPROACH 3: TOTAL SETTLEMENT WITH THE EFFECT OF CONTINUED LOWERING WATER TABLE

Approach 3 takes into account all three (3) systems of loading identified in this project, the lowering of the water table, the loading of the cover system, and the loading of the additional fill placed in 2001.

Theoretically, the ultimate settlement cannot be definitively defined if the settlement from the first cover, the second cover, and the lowering of the water table is combined. Although 100 percent consolidation has been defined to occur at time infinity, the final settlements are being calculated based on the assumption that 100 percent of the settlement has been achieved under the previous load, before the subsequent load was applied. This assumption is relatively accurate for the analysis that is being conducted in this thesis because the amount of settlement that will cause problems to the surface will occur reasonably soon after the loading and the remaining settlement will not be of enough magnitude to cause problems in the future. Using the assumption that 100 percent consolidation will occur will simplify the analysis and under-predict the final settlement. With that said, continuing to lower the water table to the bottom of the tailings may be unreasonable, but will help account for the underestimation caused by using 100 percent consolidation.

Since Approach 1 has been found to more accurately calculate the settlement caused by the lowering of the water table, and Approach 2 was structured to more accurately define the settlement caused by the loading of the soil, the combination of these key aspects from each approach will allow the total calculations to account for the three loading systems. When combining the two approaches, the settlement caused by the surface loading (Approach 2 – Figure 19) will be added to the settlement cause solely by the drop in elevation of the water table (Approach 1 – FIGURE 16).  FIGURE 21 plots Approach 2 and Approach 3. FIGURE 22 plots Approach 3 compared to the data from N4E7's settlement monument.

The settlement achieved in Approach 3 corresponds very well to the settlement data prior to the fill placement in 2001. From 2001 to 2010 the calculated settlement overestimates the actual settlement experienced in the field. This can be attributed to the assumption that $C_c$ remains constant throughout time or the amount of excess pore pressures existing within the tailings. Further testing of the tailings will refine the parameters used in the calculations and will allow for more accurate calculations.

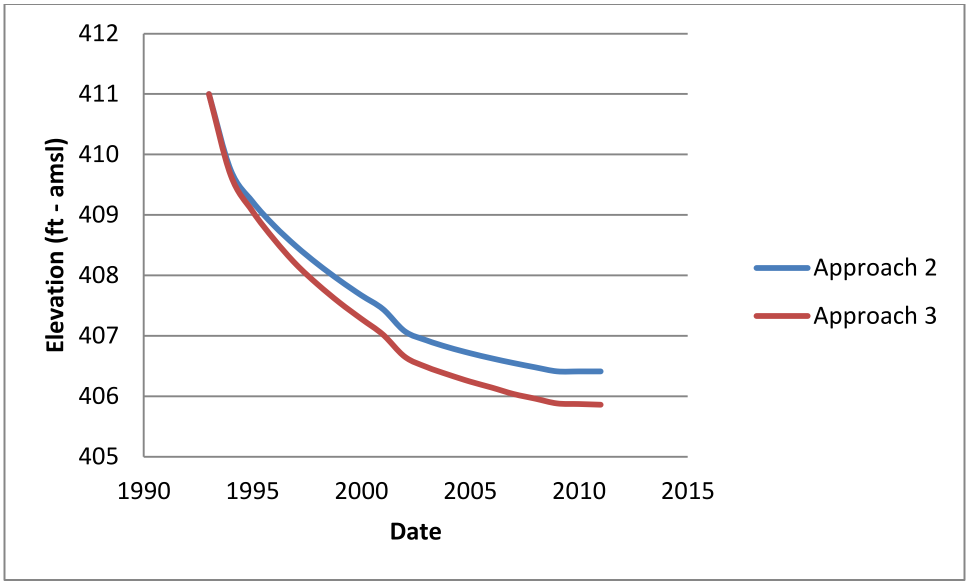


FIGURE 21 - Approach 2 and Approach 3

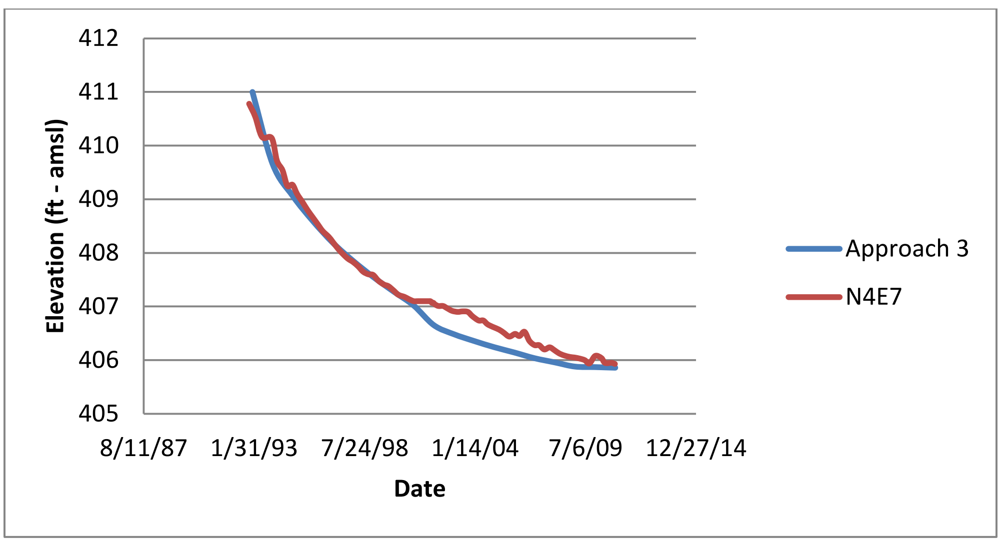


FIGURE 22 - Approach 3 with N4E7 Settlement Monument Data

Approach 2 indicates that the settlement caused by the second cover has completed and the remaining settlement will be caused by the lowering of the water table. Assuming the parameters of consolidation and rate of water table reduction (0.5 ft/yr) remain constant with the continued settlement the settlement is projected to be completed in 2051 with an additional settlement of 0.24 feet to a final tailings surface elevation of 405.62 feet. FIGURE 23A shows the current N4E7 settlement data along with the settlement through 2051. This prediction is based solely on the fact that there will be no additional loading sequences placed at the surface and that the water table will continue to drop to the base of the tailings. The remaining settlement will then be due to the final consolidation of the tailings, due in part to the drop in the water table. In the case of an additional six (6) feet of fill placed the final settlement is reflected in FIGURE 23B and it increase the total settlement by 0.33 feet and will bring the final tailings surface elevation to 405.29 feet above mean sea level. Because the assumption that the fill will not compress or settle was used, the 20 feet of fill above the tailings surface (10-foot thick fill and cover system , 5-foot thick fill in 2001, 6-foot thick additional fill in 2014) the final surface elevation will be close to 426.29 feet amsl depending on the actual thickness of the material.

This has been calculated by breaking the consolidation of the tailings into individual years and the predicted height of the perched water table at that time.

This aspect is particularly significant because it shows the effect of the water table within the tailings and how it will affect the site in the future.

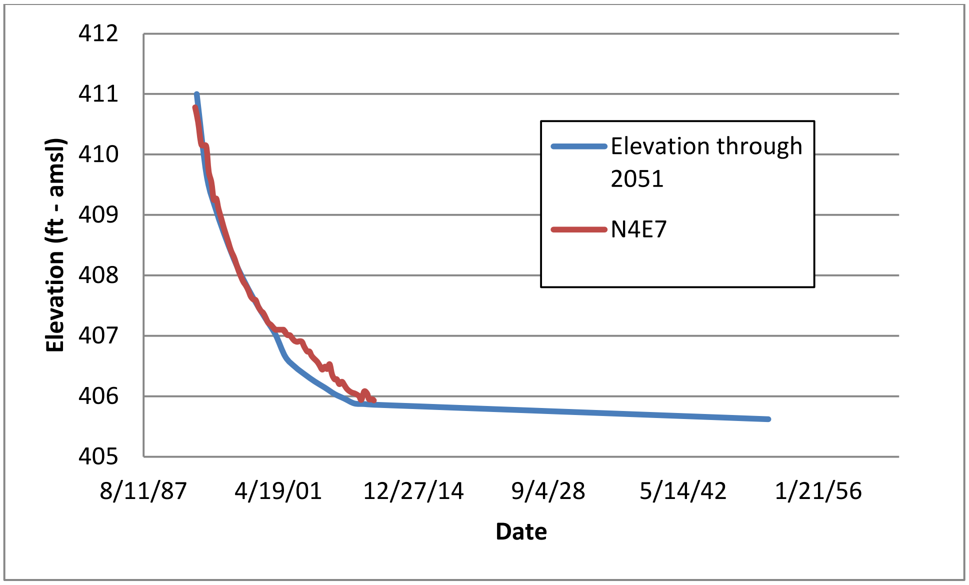


FIGURE 23A - Ultimate Settlements (Through 2051)

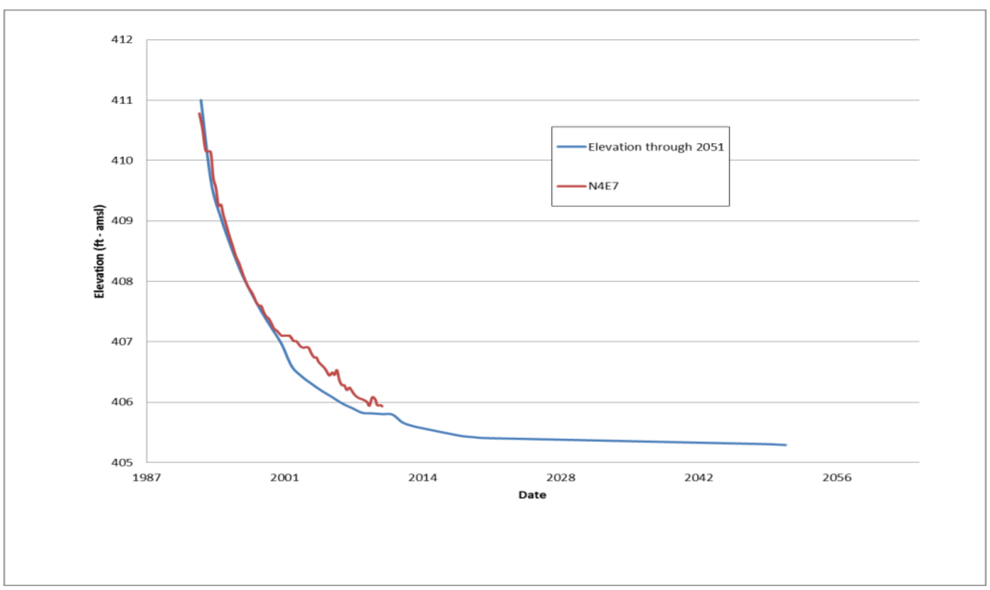


FIGURE 23B - Ultimate Settlements with additional fill in 2014 (Through 2051)

# *Chapter V: Finite Element Analysis*

An additional evaluation to assess the settlements at the site was conducted using a finite element simulation. The simulation was conducted using the code PLAXIS. This simulation will allow for a multi-dimensional assessment of the site. The site materials will be classified as linear-elastic materials and will be based on Young's Modulus (E). Young's Modulus, in the multi-dimensional analysis, is comparable to the coefficient of compressibility, in the one-dimensional analysis. Young's Modulus measures the elastic response and the ability to deform under a load. Increasing the amount of dimensions in the analysis can lead to an over-prediction of settlements. If one is not certain of the parameters, the errors produced can exponentially increase. The initial layout and material properties were constructed from reports based on past subsurface investigations.

FIGURE 24 shows the layout of the subsurface generated design with labels for each soil type. FIGURE 25 shows the material properties used for the PLAXIS design for each given soil type. FIGURE 26 depicts the generated mesh from the PLAXIS output. The PLAXIS figures in the following section show elevations from 280 feet to 425 feet (the thickness of subgrade being observed) and a length of 3600 feet (the width of impoundment)

## PHASE DESCRIPTIONS

After the materials were defined and the mesh was generated, the next step was to define the loading history. The history was broken into seven (7) stages, which can be seen in PLAXIS format on FIGURE 27. The seven (7) stages were as follows:

1. Initial Phase (1991-1992): Two (2) years of consolidation of the tailings under its own weight (FIGURE 28)
2. Phase 1 (1993): Construction of fourteen (14) feet of fill in one (1) year (FIGURE 29)
3. Phase 2 (1994): Construction of five (5) feet of fill in one (1) year (FIGURE 30)
4. Phase 3 (1995-1997): Consolidation of tailings under weight of fill for three (3) years (FIGURE 31)
5. Phase 4 (1998-2002): Consolidation of tailings under weight of fill for five (5) years (FIGURE 32)
6. Phase 5 (2003-2007): Consolidation of tailings under weight of fill for five (5) years after additional five (5) feet of fill placed in 2001 (FIGURE 33)
7. Phase 6 (2008-2010): Consolidation of tailings under weight of fill for three (3) years (FIGURE 34)

It should be noted that the elevation of the perched water table was reduced at a rate of 0.5 ft/year.

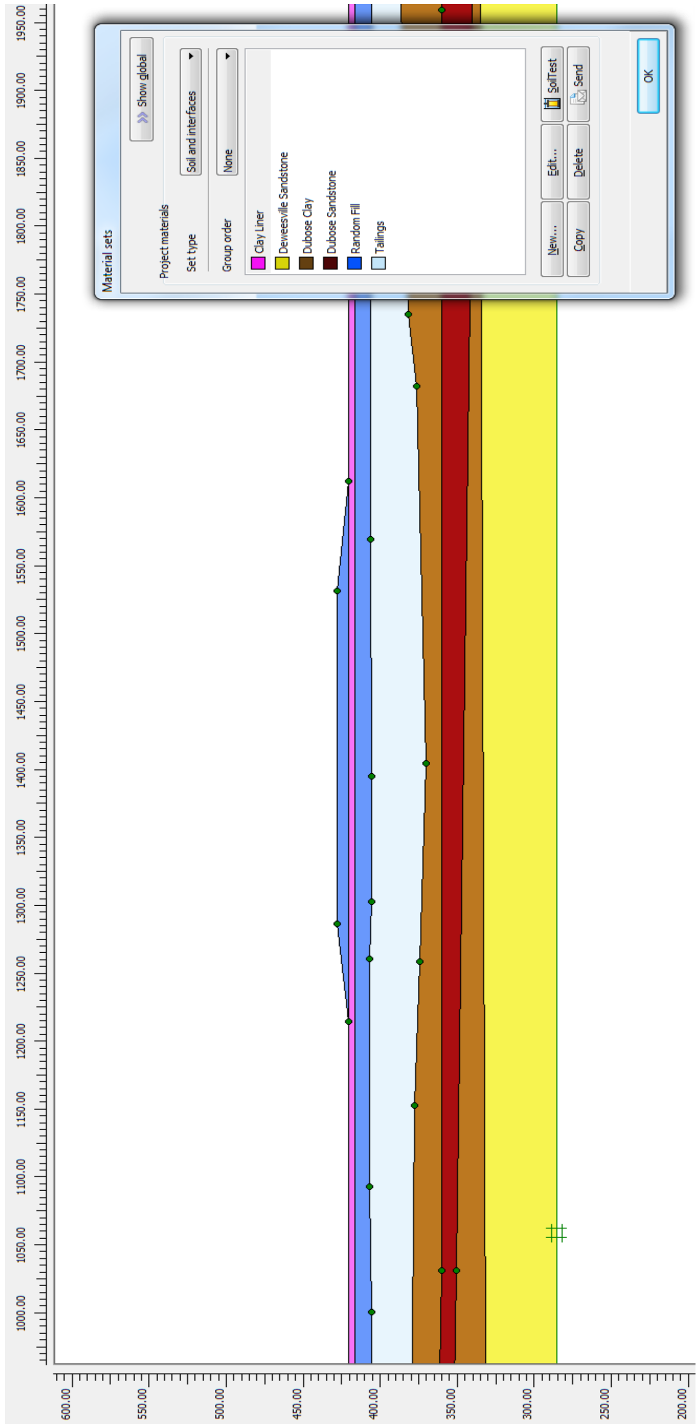


FIGURE 24 - PLAXIS Cross Section with Material Labels

| | Property | Unit | Material | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | Clay Liner | Deweesville Sandstone | Dubose Clay | Dubose Sandstone | Random Fill | Tailings |
| General | Material Model | - | Linear Elastic | Linear Elastic | Linear Elastic | Linear Elastic | Linear Elastic | Linear Elastic |
| | Drainage | - | Undrained (A) | Drained | Undrained (A) | Drained | Undrained (A) | Undrained (A) |
| | $\gamma_{unsat}$ | $lb/ft^3$ | 80 | 137 | 90 | 137 | 109 | 46 |
| | $\gamma_{sat}$ | $lb/ft^3$ | 100 | 137 | 114 | 137 | 124 | 83 |
| | $e_{initial}$ | - | 0.6 | 0.35 | 0.6 | 0.4 | 0.7 | 2.5 |
| Parameters | E' | $lb/ft^2$ | 1.60E+06 | 6.00E+08 | 1.60E+06 | 1.25E+08 | 1.60E+06 | 4177 |
| | ν' | - | 0.25 | 0.3 | 0.25 | 0.3 | 0.25 | 0.25 |
| Flow Parameters | Data Set | - | USDA | USDA | USDA | USDA | USDA | USDA |
| | Model | - | Van Genuchten | Van Genuchten | Van Genuchten | Van Genuchten | Van Genuchten | Van Genuchten |
| | Type | - | Clay | Sand | Clay | Sand | Clay | Clay |
| | < 2 µm | % | 65 | 4 | 65 | 4 | 65 | 85 |
| | 2 µm - 50 µm | % | 20 | 4 | 20 | 4 | 20 | 12 |
| | 50 µm - 2 mm | % | 15 | 92 | 15 | 92 | 15 | 3 |
| | $k_x$ | ft/day | 5.67E-05 | 16.5 | 1.65E-04 | 53.4 | 5.67E-05 | 2.83E-05 |
| | $k_y$ | ft/day | 5.67E-05 | 16.5 | 1.65E-04 | 53.4 | 5.67E-05 | 2.83E-05 |

FIGURE 25 - PLAXIS Material Properties

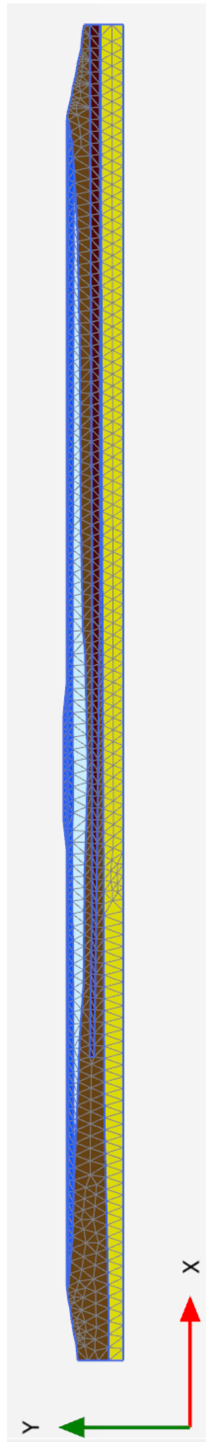

FIGURE 26 - Generated Mesh from PLAXIS

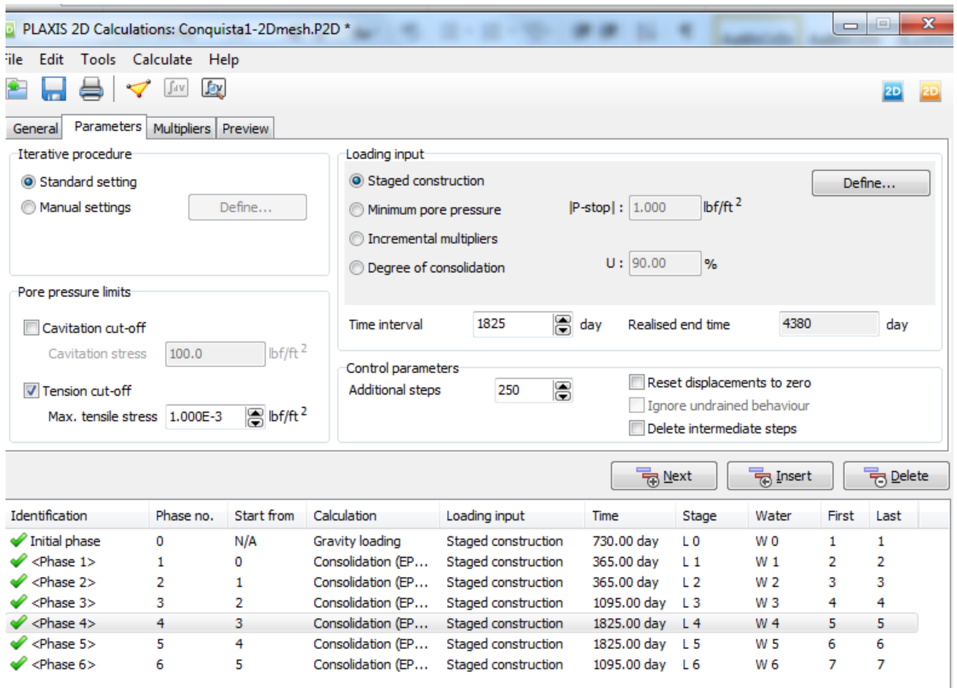

FIGURE 27 - PLAXIS Phase Descriptions

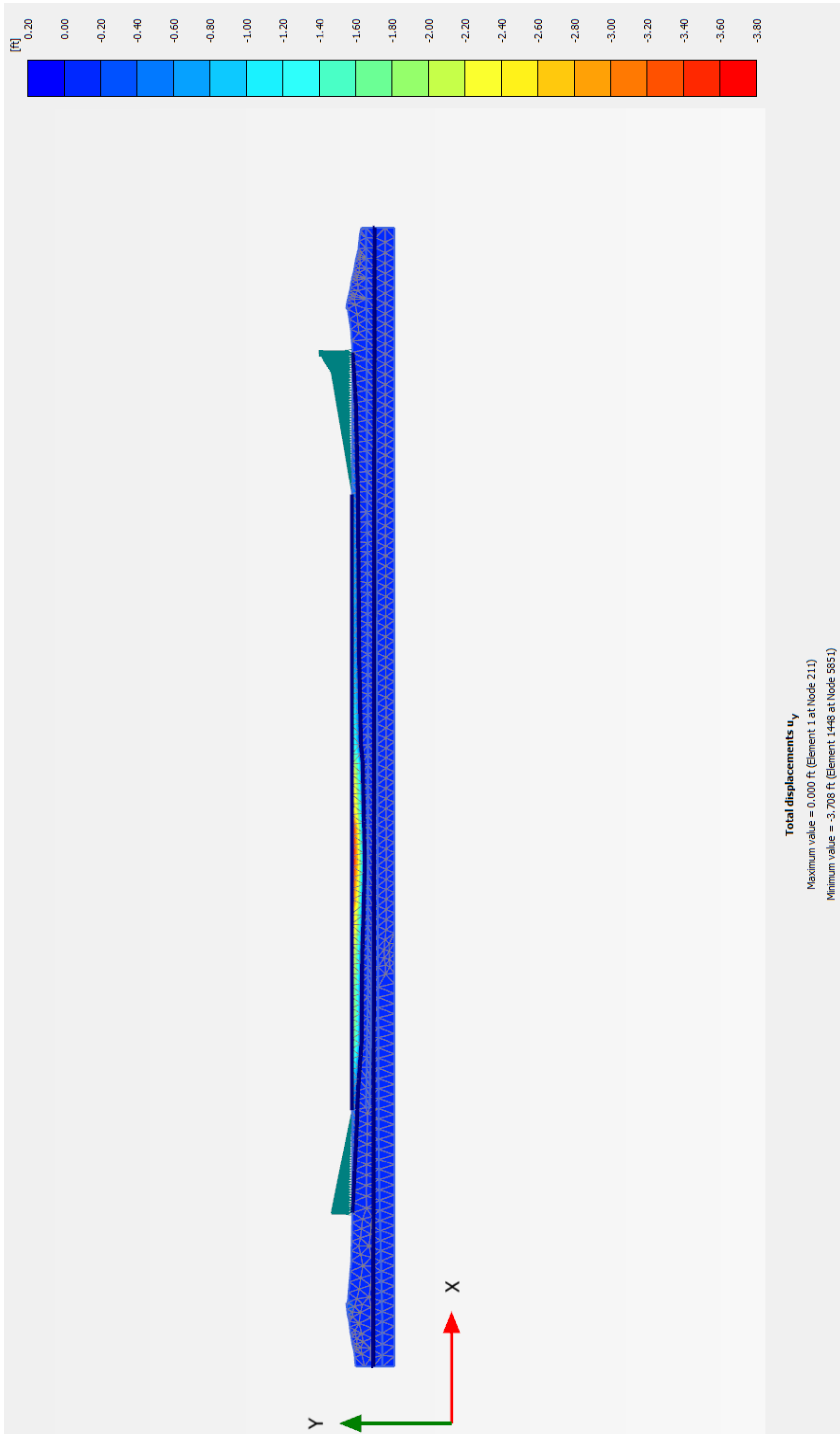


FIGURE 28 - Initial Phase

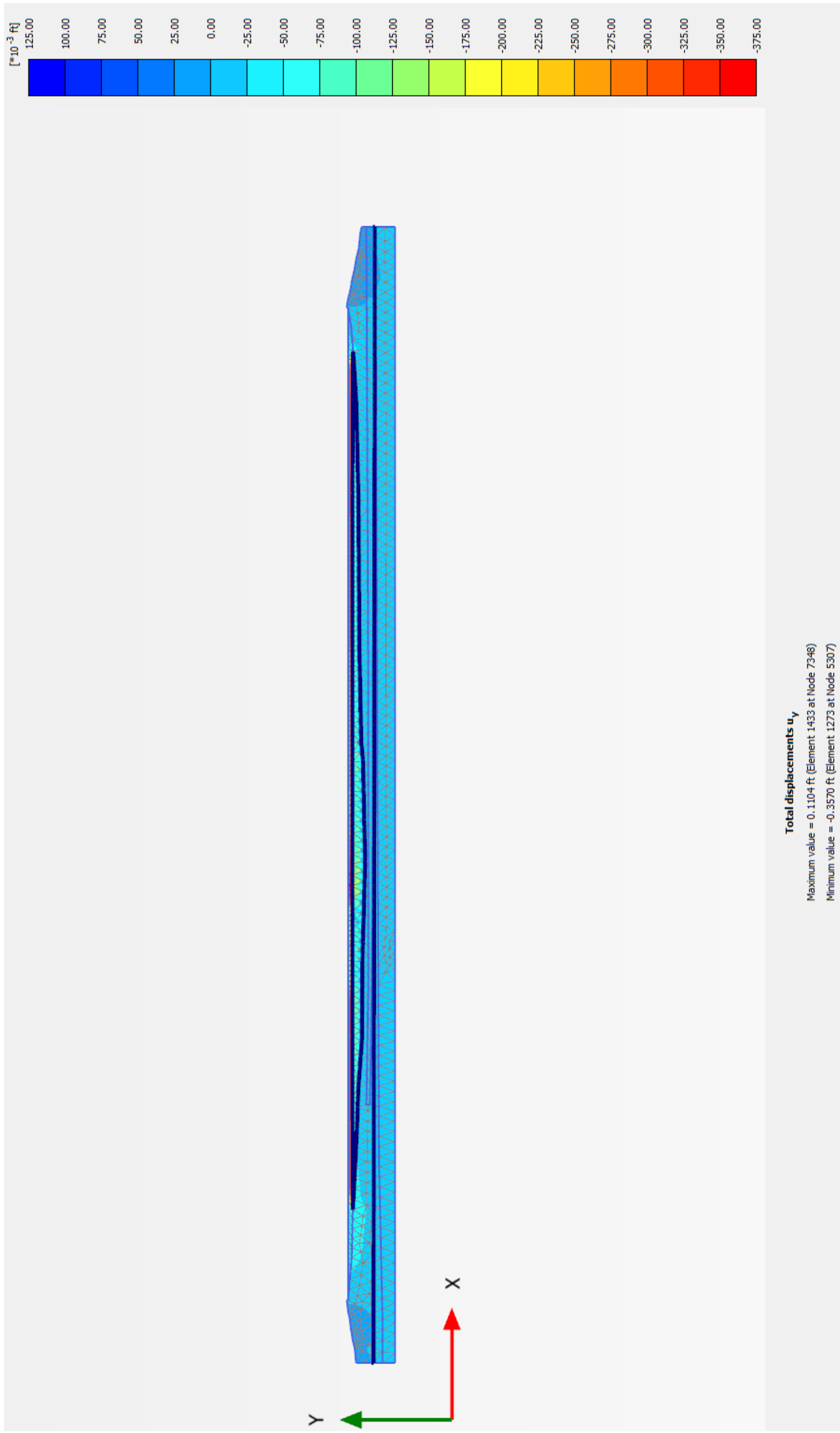

FIGURE 29 – Phase 1

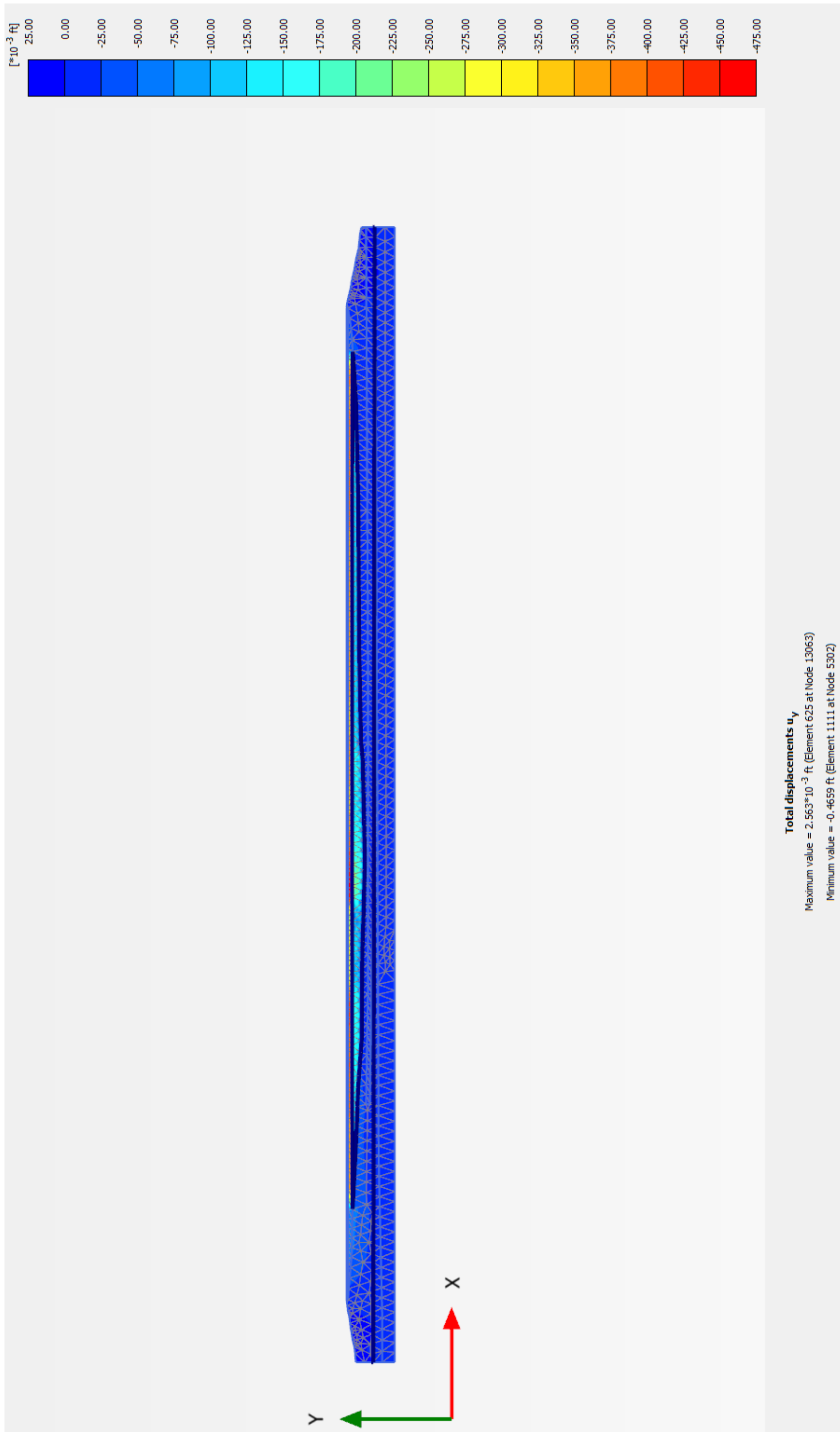

FIGURE 30 – Phase 2

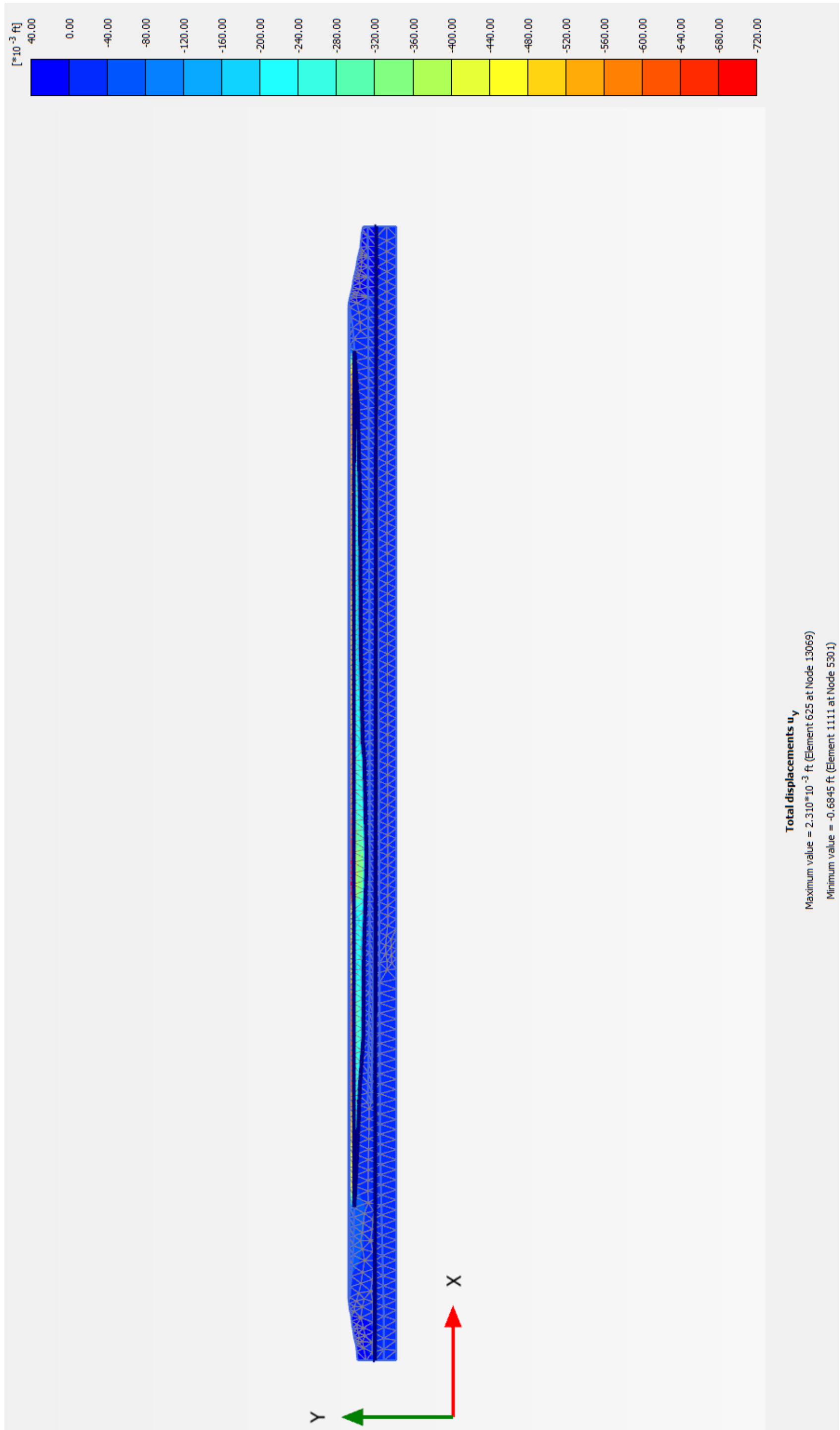


FIGURE 31 – Phase 3


FIGURE 32 – Phase 4

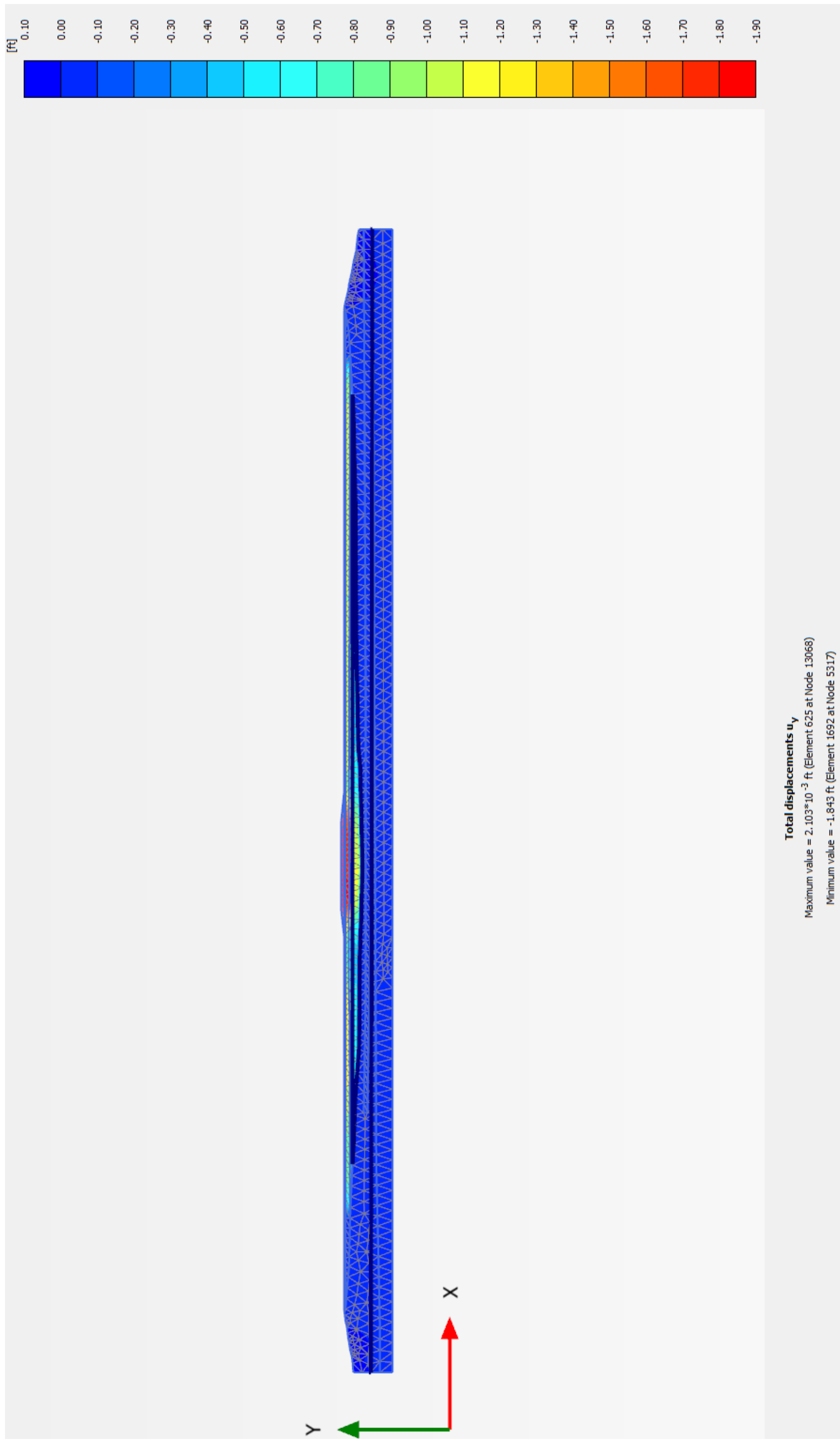

FIGURE 33 – Phase 5

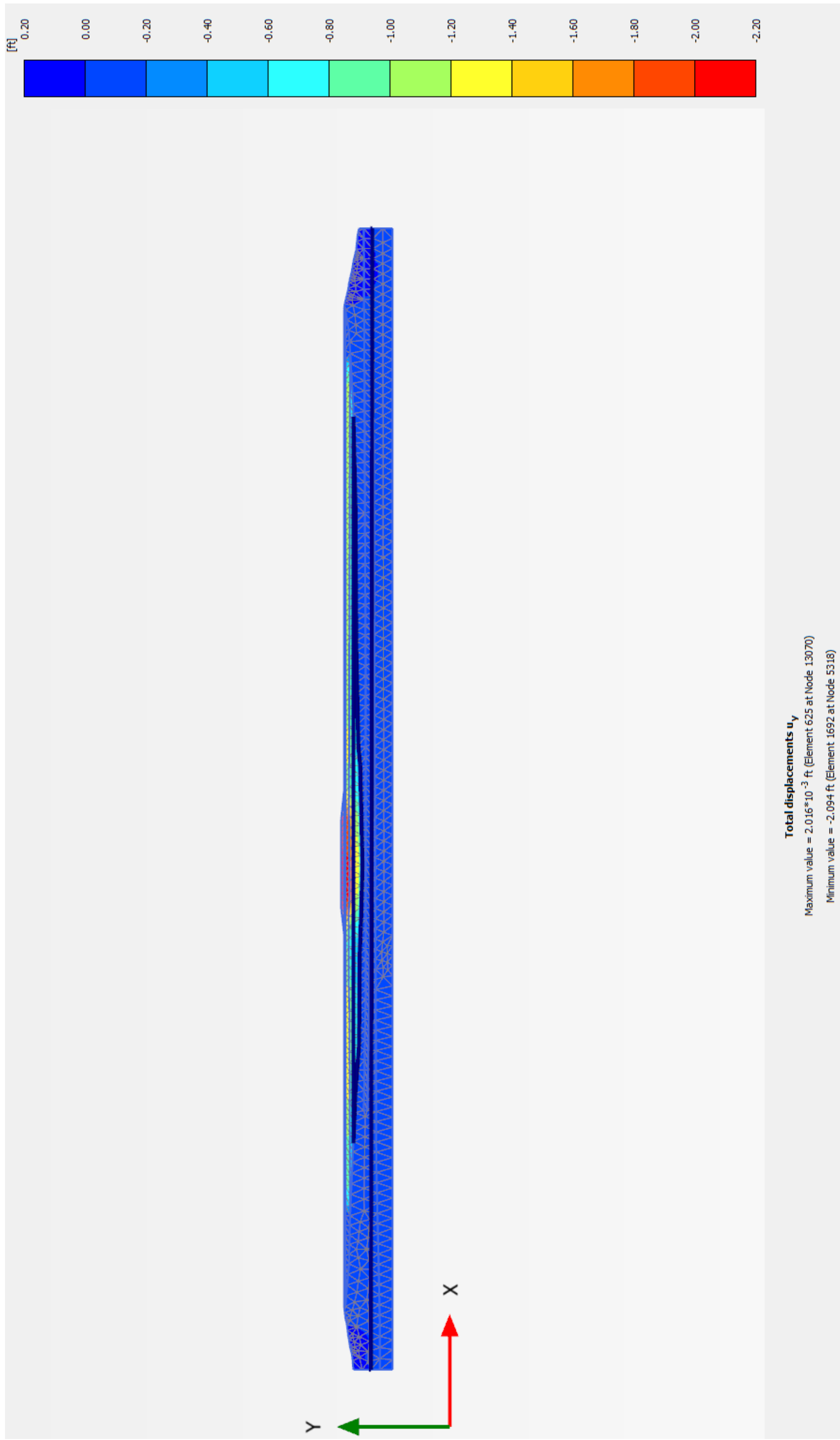

FIGURE 34 – Phase 6

# SETTLEMENT ANALYSIS

Previous finite element analysis has been completed by others on the Conquista Tailings Impoundment (Conoco Phillips, 2011). It is difficult to show the comparison of methods because the modeling has been conducted individually using different programs and reflects different aspects of the impoundment's life. One similar feature is the ultimate settlement of the material and the areas of greatest settlements. The final result presented in this report, 10.5 feet of settlement, closely mirrors past finite element settlement analyses, wherein magnitudes of 10-11 feet have been calculated. The area of greatest settlement and concern has been consistent throughout the other reports and is located above the area of thickest tailings. The settlements output by PLAXIS are shown to occur in stages (FIGURE 35). The phases break down the loading history of the impoundment. Each phase has been designed to account for the lowering of the perched water table as well as the two loading sequences from the cover and additional fill.

The initial phase creates the largest settlement due to the virgin tailings that exist below when the cover system is placed. The next three (3) phase settlements are controlled by the lowering of the water table and continued settlement of the material. In phase 4 the additional lift is placed which creates another jump in settlement felt by the tailings. The reason the settlements increase through stages 5 and 6 is due to the time duration that is being analyzed.

| Settlement By Phases | |
|---|---|
| Phase | Settlement (ft) |
| Initial | -3.708 |
| 1 | -0.357 |
| 2 | -0.4659 |
| 3 | -0.6845 |
| 4 | -1.385 |
| 5 | -1.843 |
| 6 | -2.094 |

| | |
|---|---|
| Total Settlement (ft) | -10.5374 |

FIGURE 35 – PLAXIS Settlement Data

## *Chapter VI: Conclusions and Recommendations*

### CONCLUSIONS

After months of reviewing historical documents and conversing with TCEQ, this report was compiled based on the documents provided and the conclusions drawn from the data presented within the material.

The one-dimensional analysis conducted, using the combined method of time history, is able to capture the main trend observed in the field. This has aided in identifying the significant role that the lowering of the perched water table plays in the time-dependent settlements observed in the field. The continued lowering of the water table (at a rate of 0.5/yr) has led to seemingly continued settlements at the surface, even after settlements induced by the cover placement could have reached a plateau. The total settlement that is expected from the lowering of the water table is 2.1 feet and is expected to stop in 2051.

Assuming that the tailings will reach a 100 percent consolidation, with respect to the loading of the cover and fill material, the total settlement experience by these two (2) loading conditions will be 5.5 feet. If this assumption is maintained, the settlement due to the fill material should have already reached the ultimate value. If another layer of fill material is placed, another stage of settlement will occur. By

2051, the final elevation of the ground surface will be 419.62 feet amsl without any additional work to the grading of the area. If final grading is needed (assuming 6 feet of fill) the final elevation of the ground surface at N4E7 will be 425.29 feet amsl.

The finite element simulations conducted and obtained by the use of PLAXIS are consistent with those obtained in previous studies.  The results obtained in this investigation indicate differences between the one-dimensional and finite element predictions. This is due, in part, to the fact that the input parameters and time history are less refined and more difficult to control in the finite element modeling. Both methods do show that the overall trend of monitored settlements can be explained by conventional consolidation theory, provided that the loading history is properly simulated.

## RECCOMMENDATIONS

As previously stated, further characterization of the tailings material is recommended, as it appears that significant assumptions have been made regarding the compressibility parameter and the time history of settlements. These parameters and results can be significantly refined with the availability of additional experimental and monitoring data. To date, the data that was available for consolidation analysis dates back to 1987 and is from the Western portion of the site. The values reported in those reports sets the compression index at 0.2, while the data shown in this reports yields a value closer to 0.5. With more laboratory tests on sampled tailings material, the analysis could be greatly refined.

In addition, no site historical documents were identified with infiltration analyses that predict the long term hydraulic performance of the cover system. Accordingly, characterization of the cover soils is recommended. It is unclear if the cover soils are expected to act strictly as a barrier or as an evapotranspirative component. Large cracks have been noticed in the eastern portion, while minimal to no cracking was observed on the western portion. The cracks that were observed ranged from 5-14 inches in length and between 2-4 inches in thickness. It appears that little emphasis has been placed on the predicted infiltration of water through the engineered cover. Prediction of cover performance should be conducted based on the results of the soil cover characterization.

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